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Marshall Space Flight Center

RESEARCH & TECHNOLOGY REPORT

2020

NASA/TM—20210011071 Marshall Space Flight Center RESEARCH & TECHNOLOGY REPORT 2020

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Research and Technology Report 2020

J.W. Dankanich and R.L. Frederick, Compilers
Marshall Space Flight Center, Huntsville, Alabama

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FOREWORD

At NASA Marshall Space Flight Center (MSFC), we make human space exploration possible. I'm proud to say our calling to explore is greater than ever before, and our drive to achieve our mission is unwavering.

Through the Artemis Program, we will send the first woman and next man to the Moon by 2024 with an eye toward Mars. A key goal for Artemis is demonstrating and perfecting capabilities on the Moon for technologies needed for humans to reach the Red Planet.

MSFC's technical expertise and unique interdisciplinary approach to problem solving bring scientific, technology, and programmatic expertise together to address challenges at the speed of relevance. I am proud of MSFC's role in creating solutions for so many of the daunting technical challenges we face as we move forward to the Moon. Many of these projects will lead to sustainable in-space architecture for human space exploration that will allow us to travel to the Moon, on to Mars, and beyond. Others are developing new scientific instruments capable of providing an unprecedented glimpse into our universe.

NASA has led the charge in space exploration for more than six decades, and through the Artemis program, we will help build on our work in low Earth orbit and pave the way to the Moon and Mars. At MSFC, we leverage the skills and interest of the international community to conduct scientific research, develop and demonstrate technology, and train international crews to operate further from Earth for longer periods of time than ever before — first, at the lunar surface, then on to our next giant leap, human exploration of Mars.

While each project in this report seeks to advance new technology and challenge conventions, it is important to recognize the diversity of activities and people supporting our mission. This report not only showcases the Center's capabilities and our partnerships; it also highlights the progress our people have achieved in the past year. These scientists, researchers, and innovators are why MSFC and NASA will continue to lead innovation, exploration, and discovery for years to come.

I hope you enjoy reviewing 2020's report. We have made incredible progress, and I know we will see even more advancments in 2021 as we work to make the impossible, possible.

Jody Singer

Jody Singer

Director
Marshall Space Flight Center

INTRODUCTION

It would be difficult to write any annual summary for 2020 without acknowledging the challenges unique to this year. I am proud to say that the NASA Marshall Space Flight Center (MSFC) was not forced to reconcile enlightenment on the need for diversity and inclusion, or the ability to collaborate remotely under stressing conditions. On the contrary, MSFC was on the forefront, and already implementing practices for strong diversity of thought, which results from diversity of life, as the driving force behind innovation. While other institutions experienced a down year, MSFC demonstrated a record year for innovation, with the highest number of New Technology Reports ever submitted. We have quantifiable affirmation of our efforts.

We were not without any impact. Safety was the priority, and we did limit access to laboratories and facilities for testing. However, our labor was largely able to continue through our digital tools and virtual platforms already in place. The innovators did not have the steep learning curve as many in the field. Innovators have always found a way to persevere through adversity, collaborate with external partners, and deliver even under austere conditions. The success of leaders is rarely driven by external circumstances, but rather how we react to challenges we encounter. If anything, 2020 provided an opportunity to highlight the exemplary resilience of the NASA MSFC innovators. For that, I am humbled more than ever to provide this year's Research and Technology Portfolio.

John W. Dankanich

Center Chief Technologist
Marshall Space Flight Center

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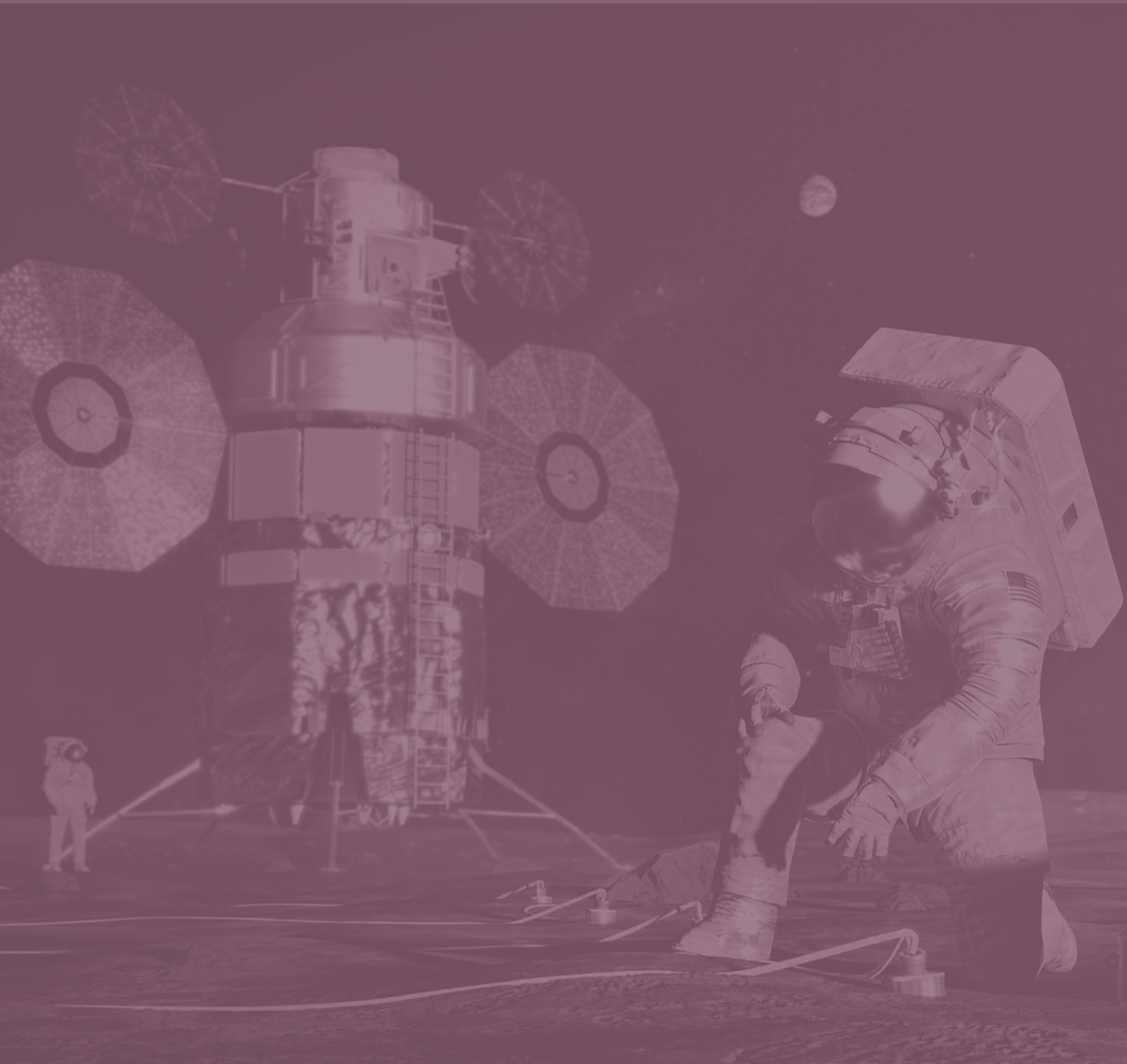
TECHNOLOGY AREA 01:
Propulsion Systems



Nuclear Thermal Propulsion (NTP)

OBJECTIVE: *To develop a low enriched uranium (LEU) nuclear thermal propulsion (NTP) system, which is the most promising advanced in-space propulsion option for crewed missions to Mars. NTP offers a safe, affordable option for an in-space transportation architecture that enables faster trip times, safeguards astronaut health, and provides abort scenarios not available from other propulsion architectures.*

PROJECT GOAL/DESCRIPTION

NASA's history with NTP technology began in the earliest days of the Agency in 1958. An NTP system offers significant advantages over other propulsion architectures for human Mars missions and in cislunar space. NTP could also enable highly advanced science and exploration missions, and power systems derived from NTP could enable a power-rich environment anywhere in the solar system (or beyond).

The current Space Nuclear Propulsion (SNP) project objective is to develop a subscale NTP engine using LEU fuel that is scalable to the Mars mission requirements for in-space propulsion. In support of this objective, additional tasks are underway to determine the best approach of accomplishing a system demonstration and identify a mitigation path for compliance with testing and launch regulatory requirements.

FIGURE 1. Model of possible future spacecraft powered by nuclear thermal propulsion.

APPROACH/INNOVATION

The use of LEU offers potential advantages for a nuclear propulsion program that includes less burdensome security regulations, similar to those for a university research reactor. The use of LEU-based fuels also enables the development effort to partner with industry and academia. The project is focused on the technology maturation of a fuel composition that could be leveraged by a point of departure subscale engine reference design baseline. In concert with the in-house fuel development and engine design evolution, a competitive procurement for a reactor design and development activity is being prepared.

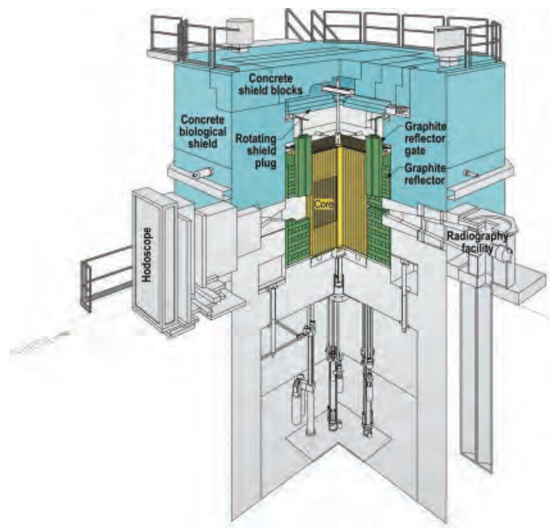


FIGURE 2. TREAT test facility.

One of the challenges to NTP development is maturing the technologies for fabrication and test of the fuel composition and element design that can tolerate the combined environments predicted in the NTP reactor core which significantly exceeds those of commercial power reactors. The project is pursuing a multi-faceted approach investigating LEU fuel systems with

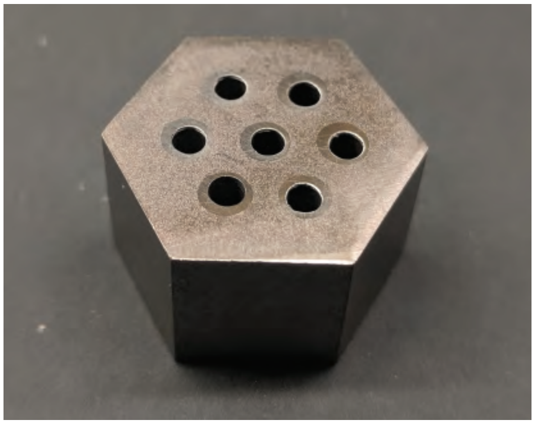


FIGURE 3. Sirius-2a cermet sample fabricated at MSFC.

refractory ceramic-metallic (cermet) and ceramic-ceramic (cercer) fuel elements, and an LEU fuel system that builds on U.S. experience and capability related to tristructural isotropic (TRISO) fuel particles. TRISO fuel compacts have been used extensively in terrestrial reactors and are of interest to multiple government agencies.

Tests of fuel samples are being performed in multiple test facilities that contribute unique separate- and combined-effects exposure to the samples, including the MSFC Compact Fuel Element Tester (CFEET), the MSFC Nuclear Thermal Rocket Element Environment Simulator (NTREES), the Idaho National Laboratory (INL) Transient Reactor Test (TREAT) Facility, and the Massachusetts Institute of Technology (MIT) reactor.

RESULTS/ACCOMPLISHMENTS

The SNP project successfully completed test campaigns for the Sirius-1 and Sirius-2a cermet fuel specimens in the INL TREAT reactor. In concert with the Sirius tests, SPS-1 and SPS-2 precursor tests were conducted in the NTREES facility to verify and provide insight into the innovative spark plasma sintering (SPS) fabrication process for nuclear fuels. All of the fuel development activities conducted by SNP were designed to leverage on the immediate risk reduction contributions of precursor events to reinforce the benefits of the following efforts and add to the collective body of knowledge that can be leveraged by development of any fission systems development pursued by NASA.

Finally, the SNP project completed a comprehensive series of internal and industry-supported formulation studies on the execution of a flight demonstration of a NTP system. The studies were useful in bounding the cost and schedule expectations for a project with that objective.

SUMMARY

NTP is directly relevant to the Agency's vision, mission, and long-term goal of expanding human presence into the solar system and the surface of Mars. As missions aim for targets farther out into the solar system, nuclear propulsion may offer the only viable technological option for extending the reach of exploration, where solar panels can no longer provide sufficient energy, and chemical propulsion would require a prohibitively high mass of propellant and/or prohibitively long trip times. NTP provides the fastest trip time of all currently obtainable advanced propulsion systems. Fast trip times will safeguard astronaut health by reducing exposure to zero gravity and cosmic radiation. Reduced travel time also reduces risks associated with reliability uncertainties inherent in complex systems, as well as those associated with life-limited, mission critical systems. NTP also enables mission abort options not available from other propulsion architectures for human Mars missions.

PROJECT MANAGER: Dayna Ise

PRINCIPAL INVESTIGATOR: Michael G. Houts

FUNDING ORGANIZATION: Game Changing Development

FOR MORE INFORMATION: https://www.nasa.gov/mission_pages/tdm/main/index.html

3D-Printed Cryogenic Strut

OBJECTIVE: *To take advantage of intricate geometries that can be produced with additive manufacturing (AM) to reduce the thermal conductivity through cryogenic support structures.*

PROJECT GOAL/DESCRIPTION

The advent of AM has revolutionized component design, allowing for innovation of new technologies and optimization of existing components. Additively manufactured lattice structures are unique geometries that reduce a component's mass while retaining desirable structural properties. Specifically in relation to thermal control, it has been shown that these structures can reduce the thermal conductivity of a component by as much as 90%, reduce its mass by up to 70%, and retain ≈45% of its ultimate strength. NASA MSFC has been conducting low-level development work on these structures for the past few years, but there are currently no commercial applications or competition in this field. NASA's Artemis Program to return astronauts to the Moon by 2024 will require advancements in technology, particularly in the area of cryogenic fluid management (CFM). The proposed effort will leverage the benefits of these lattice structures to create a cryogenic strut with strength comparable to the current state of the art (SOA), but with lower mass, cost, and improved thermal performance.

APPROACH/INNOVATION

An individual element of a lattice is called a unit cell, and AM software is able to replace sections of a computer aided design (CAD) model with repeating unit cells to form the lattice. The key to the success of this project was selecting the proper unit cell that would create a strut with the most attractive blend of mass savings, thermal performance, and structural performance. There are a great deal of unit cells available, but previous research and testing have already narrowed this field down to a handful that have the desired properties. As such, an analytical trade study was performed to assess the structural and thermal efficacy of individual unit cells. This trade study further narrowed this selection down to three thermostructurally-optimized unit cells, as seen here in figure 1.

FIGURE 1. Left to right, Octet Truss 20% Relative Density (RD), Octet Truss 30%RD, Rhombic Dode 20%RD.

The original scope of this project included the use of a small load frame to carry out tension and compression testing so that the structural analysis models could be correlated to real world test data, but due to the COVID-19 quarantine, these tests have not come to fruition.

Fortunately, it was recently discovered that a similar project studied AM lattice structures and developed structural test data, which may be used to satisfy the objectives of this testing campaign. If this data is indeed sufficient to corroborate this project's structural models, this project will move into validation testing. Validation testing will consist of testing a flight-like design of the strut up to 1,800 lbf in tension and compression, which correlates to current SOA strut qualifications. Finally, a second tension and compression test series will be performed that also tests the strut up to 1,800 lbf but uses liquid nitrogen to cool one side of the strut down to cryogenic temperatures. The low temperature experienced by the strut represents the expected operational thermal environment of the strut. The investment in this project will yield a methodology for future cryogenic strut applications, reducing the cost and lead time to develop them, as well as increasing their performance.

ACCOMPLISHMENTS

A definite lesson learned from this undertaking has been that no amount of planning can prepare a project for every contingency, as evidenced by the setbacks experienced due to COVID-19. Despite these setbacks, the project was able to perform a great deal of analysis on lattice unit cells, especially from a thermal perspective, which was previously a minimally researched area. The following general conclusions were drawn from the analysis efforts:

Thermal conductivity is:

- Greatly affected by the relative density of the unit cell.
- Slightly affected by the geometry of the unit cell.
- Unaffected by size (scale) of unit cell (a 2 mm unit cell has the same conductivity as a 10 mm cell).

Pertaining to structure:

- At constant sample size and increasing unit cell size, equivalent stiffness slightly increased, and stress decreased.
- At constant unit cell size and increasing sample size, equivalent stiffness increased, and stress decreased.

SUMMARY

To conclude, this project strives to produce a cryogenic strut which has a shorter lead time and improved performance over the current SOA. Despite setbacks caused by the quarantine, valuable analytical research has been produced. Currently, plans are being made to proceed into validation testing, which will be performed on a flight-like test article. At its completion, the project will have generated a methodology to produce cryogenic struts which can be tailored to different spacecraft applications.

PRINCIPAL INVESTIGATOR: Travis Belcher

PARTNERS: Human Landing Systems

FUNDING ORGANIZATION: Center Innovation Fund

Direct Thrust Measurements of Electric Sail Tethers

OBJECTIVE: *To directly measure thrust from an electrostatically charged tether to significantly raise the technology readiness level of the novel in-space propulsion concept known as electric sail (E-sail).*

PROJECT GOAL/DESCRIPTION

The E-sail is a propellantless propulsion system (invented by Pekka Janhunen of the Finnish Meteorological Institute) that harnesses the solar wind plasma for continuous thrust in interplanetary space. Several theoretical models of E-sail thrust performance are available in the literature, but none have been anchored to direct thrust measurements in the laboratory. Starting in 2015, MSFC demonstrated how ions interact with a biased tether element, thereby laying the foundation for scaled E-sail measurements in the laboratory. The work was part of a NASA Innovative Advanced Concepts (NIAC) project known as the Heliophysics Electrostatic Rapid Transit System (HERTS). The current project builds upon HERTS and takes it to the next level by actually measuring thrust. For a prospective propulsion system, a thrust measurement is not only a requirement but also significantly elevates the technology readiness level, thereby making an in-space demonstration mission highly attractive.

FIGURE 1. Artist concept of a deployed E-sail propulsion system.

APPROACH/INNOVATION

The concept of operations behind this project is quite simple: create a drifting plasma that simulates the solar wind and measure how much force that plasma applies to a positively biased tether (wire). Of course, applying the concept to a real-world laboratory environment is quite challenging. The forces that need to be resolved are as low as nano-Newtons. Equally daunting is the requirement to bias the tether to hundreds of volts without electrically shorting it to the vacuum chamber wall due to plasma sheath formation.

To overcome the key laboratory test challenges, the investigators have identified a special arrangement of a torsional pendulum thrust stand for measuring ultra-low forces and a gridded ion thruster to create a drifting ion plasma that will moderate the sheath formation around the tether. To maximize the effective tether area, the team developed a loosely strung pattern of tethers on both torsional pendulum paddles. The tether wires are spaced similarly to a harp instrument. When the tethers are biased, however, the electric fields will grow and overlap with each other. This will amplify the force interaction area. Drifting ions directed at the tether paddle will encounter a repelling electric field and will be deflected. The result of this interaction is that the ions will impart their momentum on the tether paddle and thereby create a force that pushes on the tether paddle and rotates the torsional pendulum. A sensitive red-laser displacement system will measure how much the pendulum rotates, which translates to the amount of force applied (using pre-test calibrations).

After the team successfully makes thrust measurements with the existing tether wire, future explorations will look at optimizing tether wire diameters and materials to improve E-sail propulsion efficiency.

RESULTS/ACCOMPLISHMENTS

The investigator team has made several important accomplishments in their effort to measure E-sail thrust in the laboratory:

(1) Moved from concept of operations to identifying and implementing facilities and hardware to make the required measurements within schedule and budget constraints.

(2) Developed and utilized a plasma model, benchmarked with previous HERTS laboratory data, to predict expected thrust levels in the laboratory.

(3) Built a bench-top torsional pendulum system featuring a unique tether wire arrangement to maximize the ion interaction area.

(4) Modeled the torsional pendulum system and performed a sensitivity analysis to optimize the ability to measure ultra-low forces.

(5) Measured the torsional pendulum performance to compare with model predictions and to enable calibration tests.

(6) Implemented a new red-laser displacement system to enable high-sensitivity measurements of the torsional pendulum rotation.

SUMMARY

The E-sail is an innovative concept of in-space propulsion. As with any propulsion system, it is critical to demonstrate measurable thrust in the laboratory, which is the primary objective of this project. As most E-sail concepts involve multi-km-length tethers immersed in a low-density solar wind environment, translating the concept to realistic laboratory scales is a challenge. To overcome this challenge, the project investigators have developed a strategy that maximizes the effective tether area on a highly sensitive torsional pendulum thrust stand. To simulate the solar wind, the team has identified a gridded ion thruster that produces a plasma with drifting ions. The laboratory plasma setup has been modeled to provide expected thrust levels (i.e., required force measurement levels). A bench-top version of the torsional pendulum thrust stand has been built and characterized using a new red-laser displacement sensor system. Following force calibration measurements of the thrust stand, the system will be setup in the vacuum chamber, and E-sail force measurements will be made.

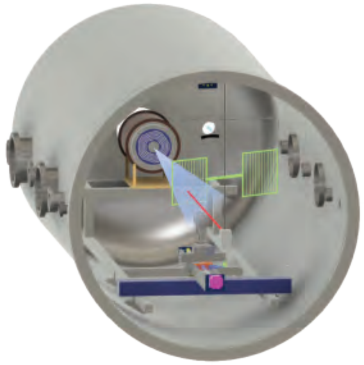


FIGURE 2. Planned MSFC vacuum chamber setup showing the ion source (light blue) incident on the positively charged tethered frame (light green) where the deflection (i.e., force) is measured by the displacement laser sensor (red).

PRINCIPAL INVESTIGATOR: Anthony M. DeStefano

CO INVESTIGATORS: Erin Hayward, Brandon Phillips

FUNDING ORGANIZATIONS: Center Innovation Fund and Technology Investment Plan

Cryogenic Thermodynamic Vent System (TVS) Augmented Injector Coupled with Cryocooler to Demo Transfer and Liquefaction

OBJECTIVE: *To demonstrate cryogenic propellant transfer and gaseous liquefaction utilizing an active cooling loop coupled to a cryocooler with previously developed additive-manufactured (AM) thermodynamic vent system (TVS) augmented injector design.*

PROJECT GOAL/DESCRIPTION

An Agency emphasis on reusable cryogenic space vehicles—especially for deep space, lunar, and potential Martian missions—has led to accelerated technology maturation efforts in the area of cryogenic fluid management (CFM). Two of these technologies are in-space propellant transfer and propellant liquefaction/storage. Typical propellant transfer operations use a continuous vented chill/fill approach; however, this is not preferred for in-space applications as zero-gravity effects reposition the liquid in the tanks, leading to potential loss of propellent when filling. To achieve what is referred as a no-vent fill case, the incoming liquid stream must be conditioned below its saturation conditions so as to minimize pressure spikes in the receiver tank.

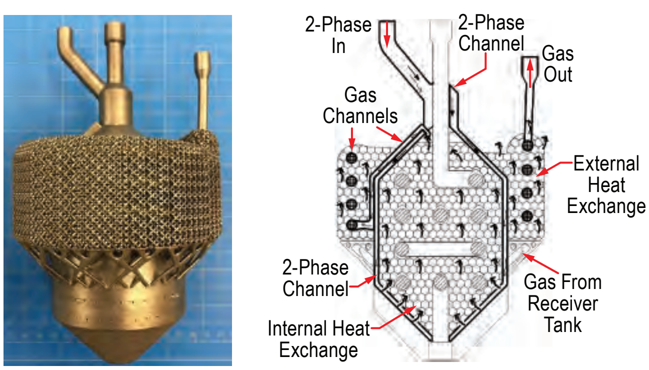


FIGURE 1. TVS injector and diagram of heat exchanger path. Image credit: O. Mireles, AIAA-2020-35805.

To achieve this, an AM injector with an integrated heat exchanger was designed to meet the needs of propellant transfer.

Past work with this TVS injector design includes successful demonstration of a vented chill/no-vent fill transfer. This effort seeks to continue the transfer maturation operations with this iteration incorporating an active cooling loop to the injector heat exchanger interface. With the potential cooling power of the cryocooler active cooling loop, it is now also feasible to liquefy incoming gaseous propellant into a receiver tank with the same TVS injector.

APPROACH/INNOVATION

Current state of the art for in-space propellant transfer is what is referred to as the charge-hold-vent method, which requires some propellant to be wasted in cooling the transfer lines as well as the receiver tank. With the addition of the active cooling loop to the TVS injector, the possibility of a complete no-vent fill is feasible.

Current state of the art for propellant liquefaction is a tube-on-tank heat exchanger coupled to an active cooling loop with a cryocooler. Although the system itself is efficient, the TVS injector with active cooling concept has the potential to be more versatile than the tube-on-tank design. Due to its compact size, the TVS injector has the ability to turn any cryogenic tank into a propellant liquefaction rig.

This effort seeks to leverage off existing NASA MSFC CFM hardware. The receiver tank and TVS injector, along with associated support hardware, will be reutilized from the previous year's injector transfer demonstration. The cryocooler and active cooling loop hardware were acquired from previous NASA propellant liquefaction testing.

RESULTS/ACCOMPLISHMENTS

Hardware assembly, integration to the vacuum chamber, and transfer/liquefaction testing are scheduled to begin in calendar year 2021.

SUMMARY

As a continuation of previous AM Cryogenic TVS Augmented Injector Experiment demonstrations, this effort seeks to further investigate the potential of utilizing the injector for not only true no-vent fill in-space cryogenic transfers but the potential for propellant liquefaction.

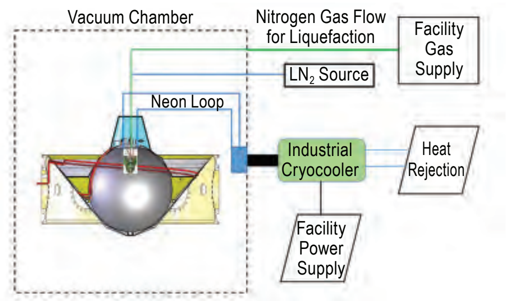


FIGURE 2. Simplified schematic of TVS injector testing.

PRINCIPAL INVESTIGATOR: Juan G. Valenzuela

PARTNERS: Yetispace, Inc.

FUNDING ORGANIZATION: Technical Excellence

Low Mass, Low Heat Leak Structures

OBJECTIVE: *To demonstrate that both the mass and thermal performance of propulsion system structures, such as tank mounts, can be improved with additive manufacturing and a novel part geometry that significantly increases the thermal conductivity path compared to the current state of the art.*

PROJECT GOAL/DESCRIPTION

Flanges and support structure can be a large part of the overall mass of a propulsion system. In addition, some systems require these structures to limit the amount of heat that is transferred from generation sources to other parts of the vehicle. This is especially true for the long-term storage of cryogenic propellants where any heat transmitted from the vehicle to the propellant causes it to boil off. Traditional solid structures, based on heritage fabrication methods, conduct heat well and can be the cause of loss of significant amounts of propellant. Reducing structure piece-part weights while still meeting the structural and thermal requirements for the system and the design-for-manufacturability capabilities of the industry is a design challenge. Additive manufacturing, selective laser melting (SLM) in particular, has opened up the design space to help tackle this task. It allows for part geometries that previous fabrication methods could not accommodate. A novel method of strut geometry that significantly increases the thermal conductivity path between the two mounting points while still maintaining structural capability has been devised. Test struts have been designed, analyzed, and manufactured utilizing this technique. Testing is planned for these struts and should allow for a direct comparison of the weight, structural capability and performance as a thermal brake to struts made using the current state of the art.

APPROACH/INNOVATION

Additive manufacturing (AM) is an established technology. However, the use of AM for topology or shape optimization of structure, in terms of structural capability and thermal performance, is an emerging concept. The approach used by the design team was to create a tank mounting strut with a geometry that significantly increased the thermal conduction path between the two strut ends. This geometry also had to meet flight structural requirements and be comparable in terms of mass to heritage tank mounting structures. For a baseline for comparison, design requirements for a tank mount strut from a previous NASA cryogenic fluid management task were chosen. This defined structural loads for torque, tension, and compression as well thermal requirements in terms of heat leak from one end of the strut to the other. Mounting points and mechanical interface requirements for the heritage design were also levied on the design of the new strut. Inconel® alloy 718 was chosen for AM of the strut, as this is the cheapest and most widely available material from SLM vendors. If the concept shows promise, different materials may be used to improve the thermal performance even more. Multiple novel strut geometries were designed that increased the length of the thermal conduction path by a factor of three compared to traditional struts. In theory, the same concept could be used to increase the length even more making the thermal conduction path even more arduous. Finite element models of these designs were completed and indicated that even using Inconel 718, which is a poor material in terms of preventing heat conduction, strut performance comparable to those manufactured with composites can be achieved with a similar or lower mass strut. Higher length factors and less thermally conductive materials will be pursued if the initial Inconel 718 design with a factor of length of three proves to be successful. Thermal testing of the prototypes in a vacuum chamber with one end of the strut exposed to cryogenic temperatures is planned. A thermocouple rake and thermal imaging will be used to assess performance compared to the analytical models.

RESULTS/ACCOMPLISHMENTS

Multiple strut designs utilizing the concept of significantly increasing the thermal conduction path have been designed and analyzed. Finite element models were created to assess the structural capabilities of these designs. Loads and mounting points for these designs were derived from those used for a composite strut that served as a tank mount for a previous NASA cryogenic fluid management system where thermal heat leak was critical. The analysis showed that the design was comparable in terms of structural capability to the heritage design. Thermal models were also created to assess the new concept to the performance of the heritage, composite strut. Thermal conduction of the new designs were comparable to the heritage design, and it is thought this can be improved even more by utilizing different materials. Multiple units have been fabricated and testing is planned in the near future to validate these models.

SUMMARY

Reducing the mass of flight hardware is every designer's goal. However, hardware also has to be designed for manufacturability which can lead to much more material being in a part than is needed to do the job. Strut designs have been completed that utilize AM and a novel geometry to significantly increase the thermal conduction path while reducing the mass of the part. Structural, thermal, and interface design requirements were generated using those for a tank mounting strut from a heritage NASA program. Prototypes of these designs have been fabricated and will be tested to compare thermal and structural performance to analytical models. If successful, the concept may allow for the reduction of mass of hardware found in many of NASA's propulsion systems. The technology may also prove advantageous in terms of reducing heat transfer which is directly applicable to many of these same systems, especially those requiring cryogenic fluid management.

PRINCIPAL INVESTIGATOR: David Eddleman and Jim Richard

FUNDING ORGANIZATION: Center Innovation Fund

Magnetically Damped Check Valve

OBJECTIVE: *To design, fabricate, and demonstrate that a damper system based on Lenz's law can reduce or eliminate high frequency chatter of a check valve.*

PROJECT GOAL/DESCRIPTION

Check valves are commonly used components in propulsion systems and industrial applications. They are passive components and designed to allow flow in only one direction. One common configuration of check valve consists of a poppet held onto a seat with a compression spring. When pressure builds, the force on the poppet face overcomes the spring force and opens the valve. These valves are typically designed for a specific set of flow conditions to which they have to be exposed in flight or operation. However, lower flow rates and pressures that the component is exposed to during processing or purge operations may be more detrimental to the valve seat and moving parts. During periods of low flow, the poppet may begin to chatter at frequencies on the order of hundreds of hertz. This common phenomenon repeatedly impacts the poppet against the main seat, causing damage to it and increasing the leakage rate of the valve. Galling, or wear, can also begin to occur between the poppet and housing leading to contamination generation or a binding failure of the component. In either case, the damage may require the valve to be replaced or serviced. The goal of this project is to develop a damper for check valves that will utilize forces produced by the Lenz effect to decrease the rate of chatter or eliminate it completely. If the damper concept serves to significantly reduce or prevent chatter, it could be used to improve reliability, life, contamination generation, and maintenance of a wide range of aerospace and industrial valves.

APPROACH/INNOVATION

The Lenz effect is caused by a magnet traveling in the copper or aluminum tube. The movement of the magnet generates eddy currents in the tube, resulting in a magnetic field and a force that opposes the movement of the magnet. The resistive force is directly proportional to the speed of the magnet; so for this application, the higher the frequency of the valve chatter, the higher the resistive force should be trying to stop it. The approach is to take a typical, poppet-style check valve and modify the design to incorporate a Lenz damper. A flow bench will be used to induce chatter in the component so that effectiveness of various magnet configurations can be tested. Testing will initially be performed with dummy weights to simulate the magnet weight and determine a baseline chatter frequency for the spring mass system. Magnets of various sizes and strengths will then be added, and the valve will be retested to determine the effectiveness of the Lenz effect as a damper to reduce or preclude chatter.

If this concept proves to be effective at reducing chatter in a check valve, a variety of other fluid components could benefit from it as well. Pressure regulators used in low-flow applications often exhibit a similar condition to check valve chatter causing the regulated pressure to become unstable. Relief valves function in a manner similar to check valves, and a Lenz effect damper could eliminate rapid reseating of the poppet, which can damage seats. Shuttle valves are essentially dual check valves that seal one of two seats from a common supply. Magnetic damping could improve the reliability of these valves as well. Last, some valves utilize internal bellows that can be easily damaged due to rapid actuation. A Lenz damper could be used to regulate this timing, thus increasing bellows and component life. All of these valve types are used commonly in industrial, oil and gas, and aerospace applications and could utilize this technology to improve their reliability and prolong life. State-of-the-art damper designs or systems for these types of components increase complexity of the design and require additional parts, moving elements, or small flow passageways that can easily become clogged.

RESULTS/ACCOMPLISHMENTS

An initial proof of concept test was performed previously. This showed reduction in chatter frequency, but the design was in no way representative of a flight-weight check valve design, nor was it optimally designed to benefit from the Lenz effect damper. This design, though not flight-like, did demonstrate a reduction in chatter frequency resulting from the Lenz effect. The current effort is to design a flight-like, poppet-style check valve with a Lenz damper. To date, the detailed design of the valve has been completed and is about to go into fabrication. Testing of this prototype is pending.

A New Technology Report has been filed with NASA on this concept. Commercial entities have shown interest in licensing the technology, and the NASA MSFC patent office has applied for a patent for this concept.

SUMMARY

The Lenz effect damper shows promise for reducing or eliminating chatter or high frequency oscillations in a number of different valve types. It is an improvement over the complex and less reliable conventional damper mechanisms that currently exist. An initial breadboard check valve was fabricated and tested, and it showed promise in utilizing the Lenz effect to reduce the chatter frequency in a low flow application. A more optimal, flight-like check valve design has been completed and fabrication of that prototype is about to begin. This prototype will be used to better understand the effects of all the variables associated with the Lenz effect on chatter frequency of a spring mass system such as a poppet style check valve. If chatter frequency is significantly reduced or can be eliminated altogether, future work to incorporate this type of damper into other valve types will be pursued.

PRINCIPAL INVESTIGATOR: David Eddleman and Jim Richard

FUNDING ORGANIZATION: Technical Excellence

Development of Tricarbide Fuels for High Specific Impulse Nuclear Thermal Propulsion

OBJECTIVE: *To develop the technology required to produce tricarbide- (uranium, zirconium, niobium carbide (U, Zr, Nb)C)-based nuclear fuel elements for operation in a nuclear thermal rocket.*

PROJECT GOAL/DESCRIPTION

Nuclear thermal propulsion (NTP) is an enabling technology for both human Mars missions and advanced science missions to the outer solar system. It offers several advantages over more traditional chemical and electrical propulsion systems. NTP utilizes fission in nuclear fuel elements to heat and expand a propellant (hydrogen) through a rocket nozzle to provide thrust. Reactor core temperatures in excess of 2,500 K are required to achieve the highest engine performance and efficiency. Solid solution uranium/refractory carbides, such as (U,Zr,Nb)C, are candidate materials for use as nuclear fuel elements. By forming a solid solution of UC with ZrC and NbC, the melting point is greatly increased, allowing operation at temperatures greater than 3,000 K, which improves the overall engine efficiency. The goal of this project is to develop and test (U,Zr,Nb)C as a potential nuclear fuel element material.

APPROACH/INNOVATION

Carbide-based nuclear fuel elements have previously been studied, beginning with NASA's Rover and NERVA (Nuclear Engine for Rocket Vehicle Application) programs in the 1960s. However, previous work utilized extrusions and heat treatments of these materials which often resulted in large grains, uneven solid solution formation, and residual carbon. In this project we instead utilize spark plasma sintering (SPS), in which direct electric current and pressure are applied to a well-mixed starting powder to consolidate it into a solid sample. With SPS, samples are heated rapidly to high temperatures, and processed samples can achieve high theoretical densities and small grain sizes.

The approach was to first study the monocarbides ZrC and NbC, and then to do some work on the binary carbide, (Zr,Nb)C. The first step in sample manufacturing was to properly prepare and mix the starting powder. Then, the powder was loaded into a die and sintered by SPS. After removal from the SPS, the samples were polished and prepared for characterization. Working with radioactive material, such as depleted uranium, requires adherence to certain safety protocols and can take longer than working with non-radioactive material. Therefore, the plan was to optimize the manufacturing and characterization processes as much as possible for (W,Zr,Nb)C, where tungsten (W) has been used as a surrogate for uranium.

Characterization of the samples began with scanning electron microscopy (SEM) and x-ray diffraction. SEM provides information on the grain structure, the grain density, and the possible existence and density of voids. Energy dispersive x-ray spectroscopy can indicate the existence of any undesired secondary phases. X-ray diffraction analysis determines the structure of the sintered samples and will also reveal any secondary phases if the SPS process did not result in the production of a single solid solution. Perhaps the most important test of the samples is their ability to survive elevated temperatures in a flowing hydrogen environment. The Compact Fuel Element Environmental Test (CFEET) at MSFC (figure 1) uses an induction coil to couple to a susceptor which radiatively heats samples to temperatures comparable to those seen in a nuclear thermal rocket. Hot hydrogen gas flows around the samples during

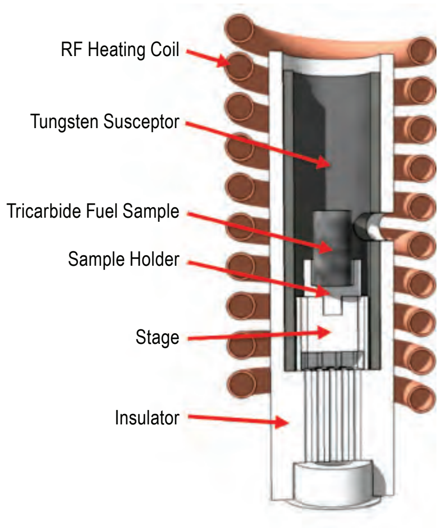


FIGURE 1. Schematic drawing of the heating assembly of the Compact Fuel Element Environmental Test (CFEET) facility.

the tests. Optical pyrometers are used to measure the susceptor and sample temperatures. Under the operating conditions of CFEET, all materials will sublimate and interact with the hydrogen gas to some extent, resulting in a measurable mass loss. There may also be other material changes in the samples. The most promising nuclear fuel candidate materials are those for which the mass loss rate during testing is minimal.

RESULTS/ACCOMPLISHMENTS

One of the objectives of the project was to obtain the processing and characterization equipment required to work on these nuclear fuel materials. A custom direct current sintering system, with a 25 metric ton pressing capability, was purchased and is awaiting installation. Other characterization equipment purchased includes an x-ray powder diffractometer, a high temperature thermogravimetric analyzer capable of operation up to 2,400 °C, and carbon and oxygen/nitrogen analyzers for use on radioactive materials. The CFEET system had both the vacuum and gas handling systems upgraded, to enhance the safety of the equipment and to improve the operational capabilities.

To date, over 30 mono, binary, and tricarbide samples have been processed and characterized. An iterative process was utilized to determine the powder processing and sintering conditions necessary to obtain samples with optimal properties. A major accomplishment was the achievement of full solubility with the tricarbide surrogate material. Full solubility is important because it means that there are no secondary phases that would have lower melting points which would lower the operational temperature capability of the material. Figure 2 shows x-ray diffraction scans for the starting powder and sintered tricarbide solid sample. Uranium-bearing samples have also been successfully sintered and work is ongoing to optimize the sintering of the tricarbide (U,Zr,Nb)C.

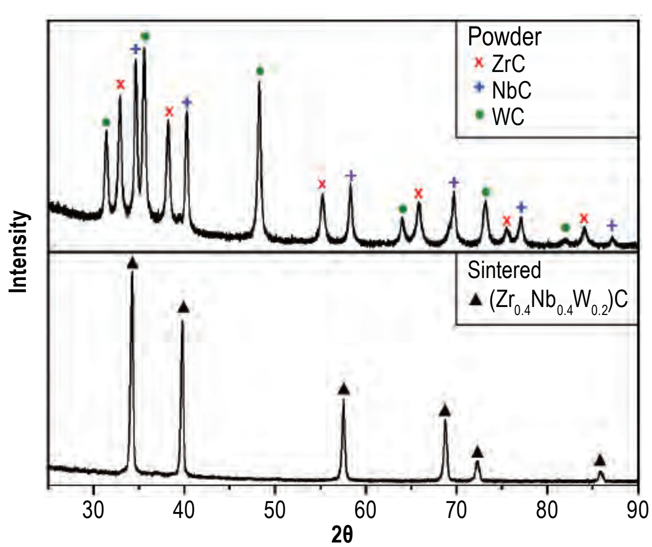


FIGURE 2. X-ray diffraction patterns of the starting powder and sintered $(Zr_{0.4}Nb_{0.4}W_{0.2})C$ sample.

SUMMARY

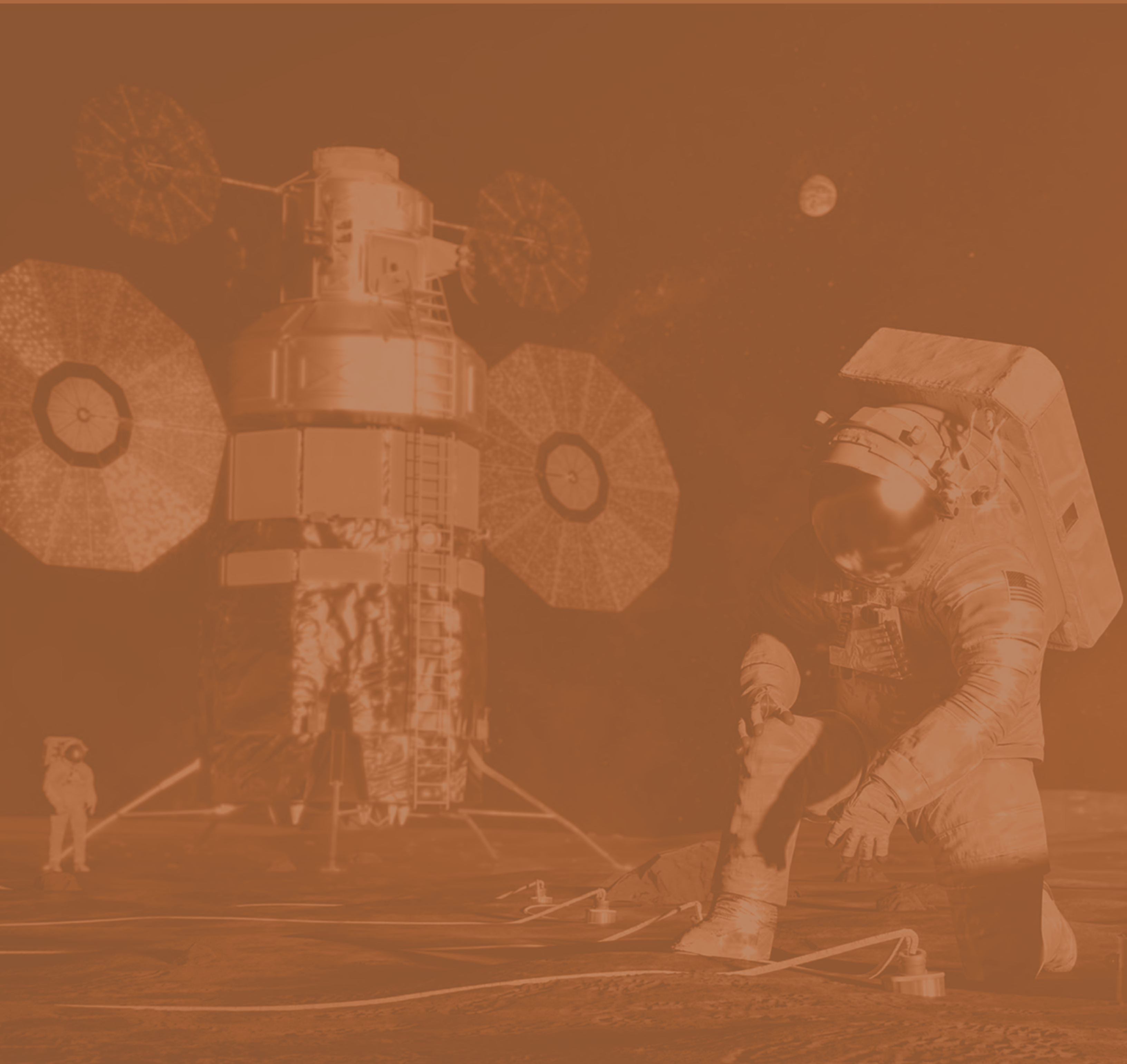
NTP has high performance potential as an in-space propulsion technology to bring cargo and crew to Mars and other destinations in the solar system. A critical aspect of bringing this new technology to fruition is the development of nuclear fuel elements that can operate in the extreme environment of the NTP reactor. Carbide-based fuel elements have the potential advantages of high operational temperatures, hydrogen corrosion resistance, and high thermal conductivity. Carbide-based fuel elements also have a relatively low density, enabling a lower rocket mass or increased payload. The goal of this project has been to develop tricarbide material using SPS as the consolidation method. To that end, full solid solution has been achieved with the uranium surrogate material. Also, hot hydrogen testing on ZrC and NbC has demonstrated mass loss rates equal to or lower than any previously reported.

PRINCIPAL INVESTIGATORS: Martin Volz and Ryan Wilkerson

PARTNERS: University of Alabama in Huntsville and Los Alamos National Laboratory

FUNDING ORGANIZATION: Technical Excellence Program

TECHNOLOGY AREA 02:
Flight Computing and Avionics



Additively Manufactured Titanium Solid Rocket Motor Cases

OBJECTIVE: *To investigate the feasibility of using of electron beam additive manufacturing (EBAM) for 3D printing titanium solid rocket motor (SRM) cases to reduce lead time.*

PPROJECT GOAL/DESCRIPTION

Lead times for SRM manufacture can be almost three years with motor case forgings requiring a significant portion of this lead time. Forgings can take 6–12 months to create, machine, and shape. This has placed two recent SRM procurements on or near the critical path of the Europa Lander and the Mars Ascent Vehicle projects with NASA Jet Propulsion Laboratory (JPL). Additively manufacturing metallic SRM cases could reduce schedule from 12 months to 2 months. To apply this technology to NASA applications, testing needs to be completed to confirm the quality of additively manufactured (AM) titanium versus standard forgings.

APPROACH/INNOVATION

To prove the feasibility of this technology, three 20-in diameter domes along with witness specimens will be fabricated using EBAM. Two of the domes will be welded together to form a spherical case test article. The third dome will be welded to a flat plate to form a half-case test article. The finished test articles will be hydroburst tested, and the witness specimens will be tensile tested. Stress analysis will inform the design of the half-case and better predict the burst pressure failure. Testing aims to confirm the quality of AM titanium as compared to standard forgings for use in SRM cases.

FIGURE 1. Titanium dome being fabricated using EBAM, by FAMAero.

RESULTS/ACCOMPLISHMENTS

For this task, MSFC's propulsion department has partnered with Future Additive Manufacturing Aerospace (FAMAero) as the manufacturer for the test articles. The vendor was consulted for the design of the printed parts and budget. Additive manufacturing experts at MSFC were consulted for dome and witness sample designs as well as the general approach. Propulsion structural analysts at MSFC provided guidance on test article design and performed stress analysis to help refine the test article designs as well as

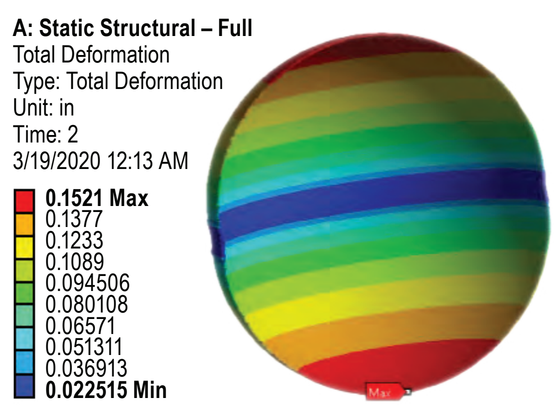


FIGURE 2. Finite element analysis of spherical case design, courtesy of the Structural Mechanics Team in MSFC's Propulsion Systems Department.

better predict the failure pressure during the hydroburst tests. After a multi-month delay caused by the COVID-19 pandemic, FAMAero was able to manufacture the parts for the test articles. This was completed with no issues.

Going forward into FY 2021, FAMAero will have the domes machined down to design specification. Due to the innate way EBAM lays down material during printing, there is excess material on the domes that requires final machining. After machining, the domes and witness sample will be sent to MSFC for testing. The domes will be fitted with fill and leak ports for the hydroburst tests and then welded. Propulsion structural analysts at MSFC will be consulted for the placement of the test ports to reduce risk of an inadvertent design failure during testing. The tensile specimens will be cut by wire electrical discharge machining (EDM) and provided to material test experts at MSFC for tensile testing. The hydroburst tests of the completed cases are projected to occur in January 2021. These tests will take place in the Propulsion Research Laboratory at MSFC with the Advanced Propulsion Branch administering the test.

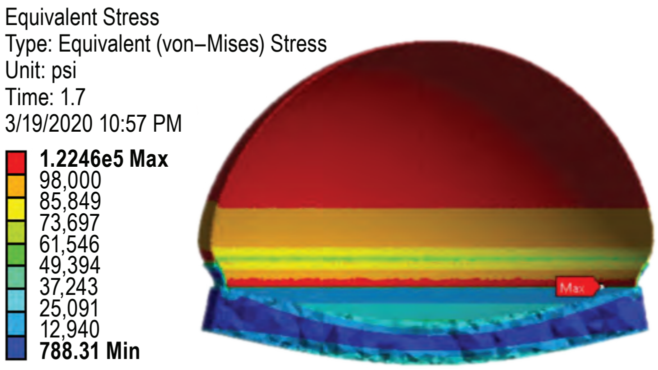


FIGURE 3. Finite element analysis of hemispherical case design, courtesy of Structural Mechanics Team in MSFC's Propulsion Systems Department.

SUMMARY

Solid rocket motor case forging can take 6–12 months to complete. This typically long lead time has pushed project SRM procurements toward the critical path. Additively manufacturing SRM cases could reduce the lead time down to 2 months. During FY 2020 and the COVID-19 pandemic, a 20-in diameter spherical case and half-case were designed, stress analyzed, and printed. Looking toward FY 2021, the test articles will undergo machining and assembly, after which hydroburst testing is tentatively scheduled to be performed in January 2021. Tensile specimens will be cut from a printed witness sample and tested for material properties.

PRINCIPAL INVESTIGATORS: Lisa McCollum, Nicholas Briggs, Kathryn Wiedow, and Aditya Patel

FUNDING ORGANIZATION: Technical Excellence

Deflection of Plasmas Using Magnetic Nozzles

OBJECTIVE: *To demonstrate the ability of a shaped magnetic field to collimate an expanding plasma for propulsion.*

PROJECT GOAL/DESCRIPTION

The goal of this project is to design and test subscale magnetic nozzles for plasma deflection. The end application of this research and technology is to support pulsed fusion or fission/fusion hybrid propulsion systems such as the pulsed fission-fusion (PuFF) concept currently being studied at NASA MSFC. This project is being developed in conjunction with numerical modelling work. Both efforts are primarily conducted at the University of Alabama in Huntsville (UAH) with oversight by MSFC.

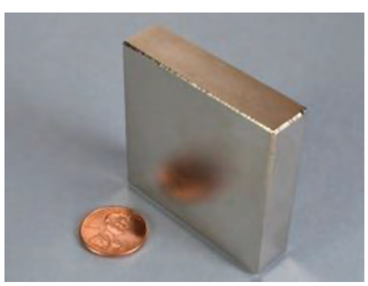
APPROACH/INNOVATION

A magnetic nozzle nozzle uses High Temperature Superconducting (HTS) thrust coils to produce a strong magnetic field (1–40 metric tons within 10 cm of the coils). These field lines direct an expanding plasma out of the nozzle and produce thrust. The nozzle elements will be heated by the photon and neutron radiation from the plasma that can reach temperatures that well exceed the capabilities of any structural materials. Thus the nozzle must be cooled, and the thrust coils must be supercooled (below 77 K) to function.

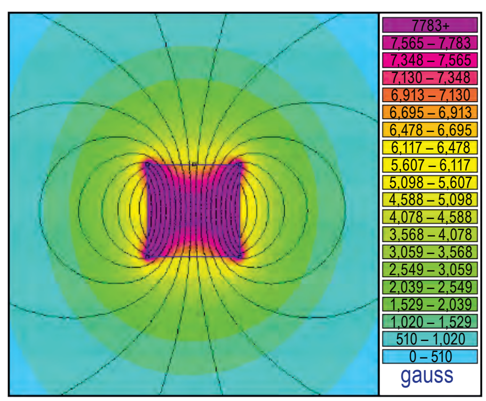
One of the challenges is to demonstrate that a magnetic field will deflect an incoming plasma. There has been some discussion in the literature on whether the incoming plasma would reflect or become trapped on the magnetic field lines. This issue has separated the efforts of several propulsion concepts, both nuclear based and those interacting with the plasma ejected by sol.

RESULTS/ACCOMPLISHMENTS

During Fall 2019, we focused on testing the plasma jet in the vacuum chamber and preliminary deflection tests with rare Earth permanent magnets. A high voltage pulse generator, generated a 5 kV pulse in 15 sccm argon in a vacuum chamber. This plasma jet was directed at a commercial permanent magnet. A set of 2- by 0.5- by 2-in neodymium (NdFeB)



(a)



(b) Grade = N42 Width = 0.5 in
Length = 2 in Thickness = 2 in

FIGURE 1. Plasma deflection of the ≈1 eV plasma jet (a) photograph and (b) simulated magnetic field curves using FEMM.

(a) (b)

FIGURE 2. The pulsed plasma jet (a) in open vacuum and (b) against the permanent magnet. Clear evidence of deflection is seen.

N42 magnets with nickel-copper-nickel coating magnetized along long direction was purchased. The max surface field from the vendor specification is 6367 G, which is the order of magnetitude desired for plasma deflection of the ≈1 eV plasma jet. A picture and the simulated magnetic field curves using the program Finite Element Method Magnets (FEMM) is show in figure 1.

The UAH experiment above was considered the first level effort, with a higher power effort planned at MSFC. Here, the team created an inverse z-pinch that would create a toroidal plasma at roughly an order of magnitude higher power level. That effort is underway but has been paused due to lack of access to MSFC labs due to the ongoing pandemic.

SUMMARY

Figure 2 shows clear deflection of the plasma jet. Delays due to COVID-19 have hampered further efforts. However, the UAH team has shown stop motion deflection of the incoming plasma further demonstrating clear nearly spectral deflection. Future efforts will use plasmas and magnetic field at higher power levels to closer approach the expected conditions for concept propulsion systems.

PRINCIPAL INVESTIGATOR: Robert Adams

PARTNERS: University of Alabama in Huntsville, Kunning Xu

FUNDING ORGANIZATION: Center Strategic Development Steering Group

FOR MORE INFORMATION: www.nasa.gov/puff

Wireless Sensor Dots for Advanced Vehicles

OBJECTIVE: *To mature wireless sensor technologies for testing and vehicles.*

PPROJECT DESCRIPTION

This project aims to create advanced wireless sensors for harsh environments. Nodes for strain gauge, thermocouple, resistive temperature devices (RTDs), and pressure sensors are being created and tested. These sensor nodes will be integrated with graphical user interface software for seamless display of sensor data and control of sensor nodes. Software development of a time division multiple access (TDMA) algorithm is also under development and testing to make sure all the data of a high sample rate, high-density sensor network, gets through. Another goal of this project is to reduce the overall size of these nodes to 1-in-diameter nodes.

ACCOMPLISHMENTS

Current accomplishments include an advanced strain gauge sensor with over-the-air (OTA) gain control, automatic calibration, and automatic zero capabilities. A wireless RTD sensor; wireless K-type thermocouple sensor; and a wireless, digital, integrated pressure sensor have been designed, built, programmed, and tested. Any other type of thermocouple besides K-type is available with a minor component change. An analog pressure sensor node has been designed and built but is in the testing phase. This sensor will fit different applications than the digital integrated pressure sensor. Each of these sensors will need to be fielded and handled, so enclosures for each sensor have been designed and manufactured and are undergoing fit check and handling review. Software

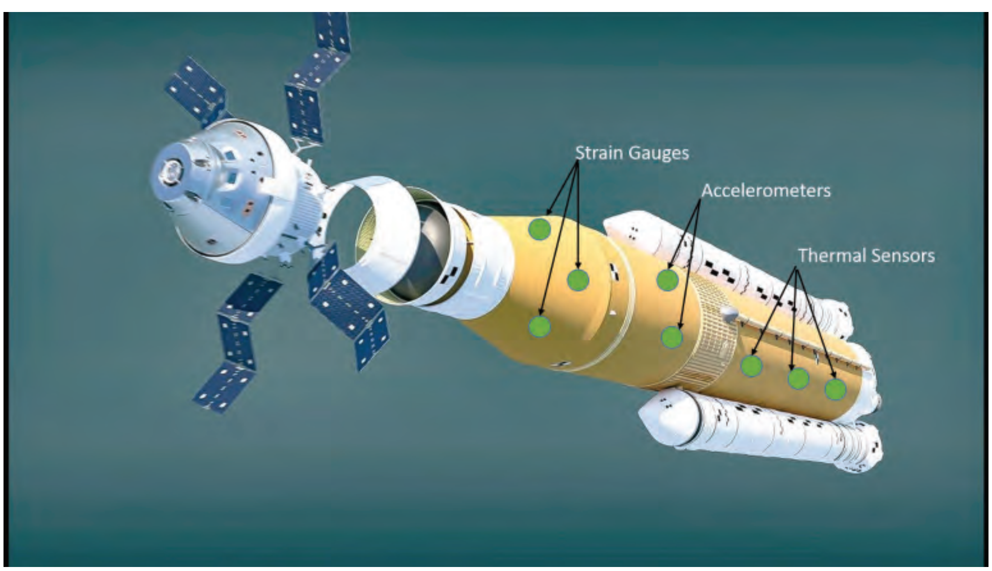


FIGURE 1. Space Launch System with sensor nodes labeled.

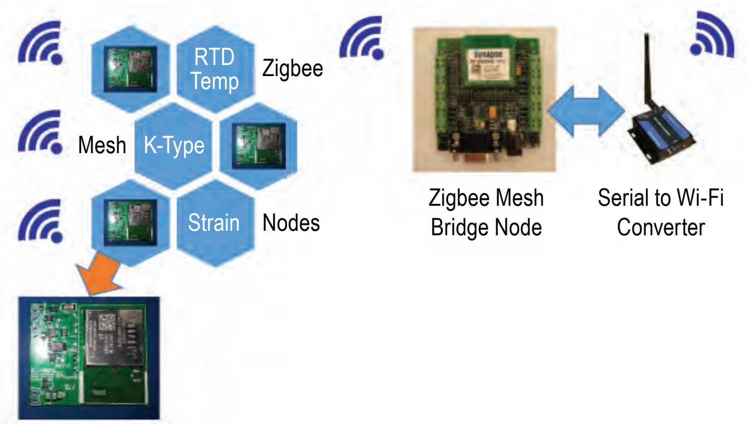


FIGURE 2. Strain gauge sensor.

to handle all the data, commands, and display from these sensors has also been developed and tested. It is currently to the level of being able to command and handle the data in raw form with minimal graphics for display and commanding. More advanced dashboards for display and commanding are in process.

SUMMARY

Wireless Sensor Dots for Advanced Vehicles is a multi-year effort to mature technology readiness level (TRL) of technologies needed to enable reliable wireless sensor use in harsh, and radio-frequency-interference laden applications and environments.

FIGURE 3. Sensor nodes end-to-end architecture.

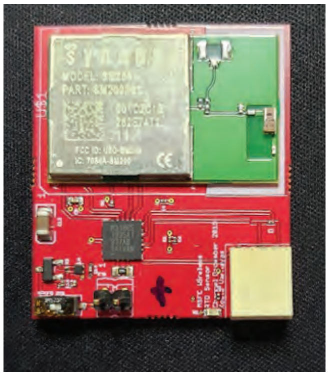


FIGURE 4. RTD sensor.

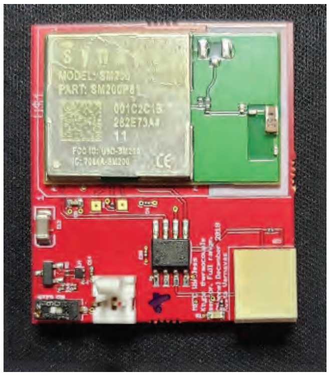
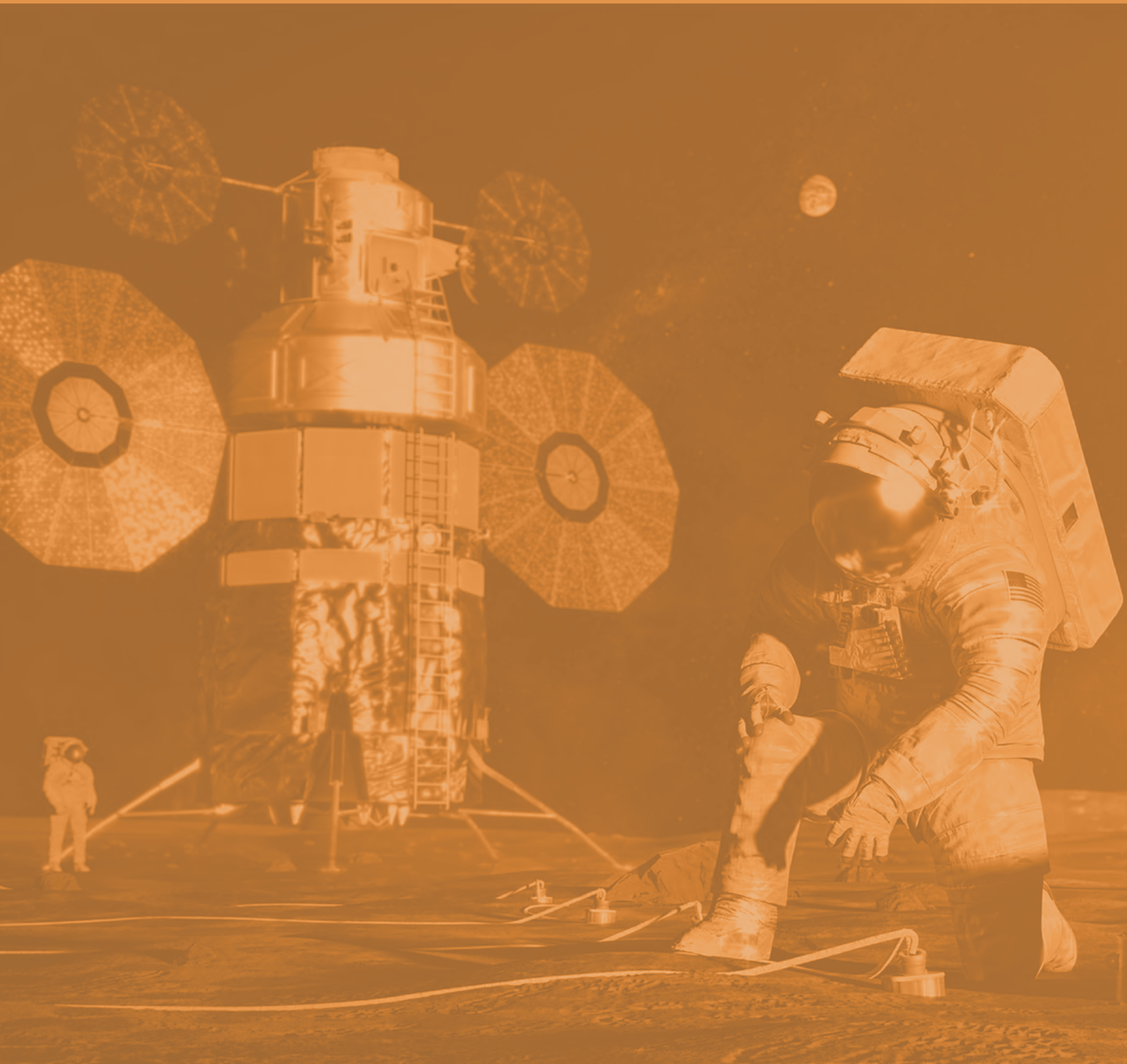


FIGURE 5. K-type thermocouple sensor.

PRINCIPAL INVESTIGATOR: Kosta Varnavas
FUNDING ORGANIZATION: Technical Excellence

TECHNOLOGY AREA 03:

Aerospace Power and Energy Storage



The Lightweight Integrated Solar Array and anTenna (LISA-T) Pathfinder Technology Demonstrator (PTD)

OBJECTIVE: *To demonstrate the deployment, operation, and environmental survivability of the Lightweight Integrated Solar Array and Antenna (LISA-T) power generation and communication array in a representative operational environment.*

PROJECT GOAL/DESCRIPTION

Satellite miniaturization continues to create lower-cost, faster-paced, and higher risk-tolerant options for space missions. Small spacecraft continue to grow in popularity and are becoming of interest to scientific, exploratory, and commercial missions alike. The large body of research and development within government, academia, and industry has greatly advanced small spacecraft technologies and, as a result, mission capabilities. However, electrical power systems have not commensurately increased in capability, creating a bottleneck in bus design and, ultimately, payload capability. This is driving the need for advanced power generation, storage, and distribution designs. LISA-T is being developed, in partnership with NeXolve Holding, LLC, (Huntsville, Alabama), to fill the power generation portion of this technology gap.

FIGURE 1. LISA-T PTD mission configuration. LIAS-T array shown deployed from the 6U host CubeSat bus.

LISA-T provides a compact, lightweight, efficient, and affordable power generation system with an integrated antenna for small spacecraft missions. LISA-T generates >300% more power per mass and volume than state-of-the-art options, vastly improving electrical power availability on small spacecraft. The technology will enable both highly capable, near-Earth small spacecraft missions as well as the capability for small spacecraft to operate deeper into space than currently possible. This is essential for science applications such as space weather monitoring concepts, national defense applications, as well as small spacecraft flagship mission support such as communication relays or ancillary spacecraft to capture additional science during the mission.

To date, LISA-T has been developed through technology readiness level (TRL) 6. Prototype arrays have been fabricated and tested in a comprehensive set of relevant space environments. To prepare the array for mission infusion and ubiquitous use, an in-space technology demonstration is currently being prepared. The LISA-T Pathfinder Technology Demonstration (PTD) is a payload comprising of a LISA-T array along with supporting electronics, data collection systems, and other hardware that will fly on a 6U CubeSat as part of NASA's Small Spacecraft PTD series of rapid demonstration missions. LISA-T PTD will demonstrate the deployment, operation, and environmental survivability of LISA-T in low Earth orbit LEO). The mission will prove out the LISA-T technology, achieving TRL 7, ensuring the power generation array is ready for mission designers to take advantage of the >300% higher power generation for small spacecraft.

APPROACH/INNOVATION

To fill the technology gap, LISA-T utilizes thin-film materials to do more, from less. The use of thin-film based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option; however, the materials, cells, and deployment systems have not been available to make them a reality. Thinner materials yield both mass and volume savings, enabling more power to be generated from the same mass and volume allocation. Perhaps

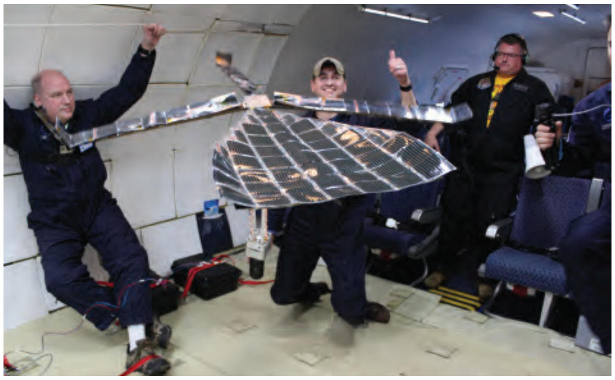


FIGURE 2. LISA-T Zero-G successful simulated weightlessness deployment test. LISA-T shown deployed on final parabola, without gravity offloading, supporting itself in weightlessness.

just as important for small spacecraft, the mechanical flexibility of thin films lends itself well to stowage and deployment schemes, allowing novel folding of the array into the spacecraft for launch as well as unfolding of the array once in space. LISA-T is utilizing advanced solar cells being developed in industry (for example, inverted metamorphic multi-function cells) coupled with advanced, space-rate polyimide materials manufactured by our partner, NeXolve Holding, LLC., to form the basis of LISA-T. These cells and core materials are backed by a novel multifunction mechanical system, which provides both the structural backing as well as deployment (unfolding) forces for the array.

RESULTS/ACCOMPLISHMENTS

Several accomplishments have been made over the last year to prepare the LISA-T technology for the PTD missions. Early in FY 2020, the LISA-T PTD array configuration was successfully tested under a simulated weightless environment utilizing a parabolic flight on Zero-G (Dumfries, Virginia). The team flew ≈60 parabolas testing 4× deployments to ensure proper mechanical operation in a weightless environment. For thin-film low mass systems, this testing is a necessity as the forces induced by gravity during ground-based mechanical testing greatly affect the system results, hindering the ability to predict the mechanical performance of the array in the microgravity of space.

Also in FY 2020, samples of the LISA-T array, which spent ≈1 year exposed to the LEO space environment on the Materials on International Space Station Experiment Flight Facility (MISSE-FF) were successfully returned to Earth. Premeasurements of the samples were taken before launch to the International Space Station (ISS) early in FY 2019, and post-exposure measurement will now be conducted. This sample testing will allow the team to correlate ground-testing models to real in-space exposure data, ultimately allowing end users of LISA-T to better predict performance and survivability for their missions.

Lastly, the LISA-T PTD team successfully completed a preliminary design review (PDR) in August 2020 and has begun working toward a Spring 2021 critical design review (CDR). The successful PDR shows a viable payload design to demonstrate LISA-T in space and prepare the technology for mission uses. The LISA-T PTD payload is currently working toward the TRL 7 in-space demonstration in late 2022 to early 2023.

SUMMARY

The LISA-T array will enable highly capable small spacecraft to operate near-Earth as well as deeper into space through improved power generation and communication capabilities on the same deployable array. The LISA-T PTD mission will demonstrate this array, proving it out for future mission use. The deployment, operation, and environmental survivability of LISA-T will be tested. This mission, combined with ground-based testing, the parabolic testing, and the MISSE-FF exposure modeling will enable LISA-T to provide >300% improved power generation to small spacecraft and usher in a new class of low-cost, fast-paced, risk-tolerant missions.

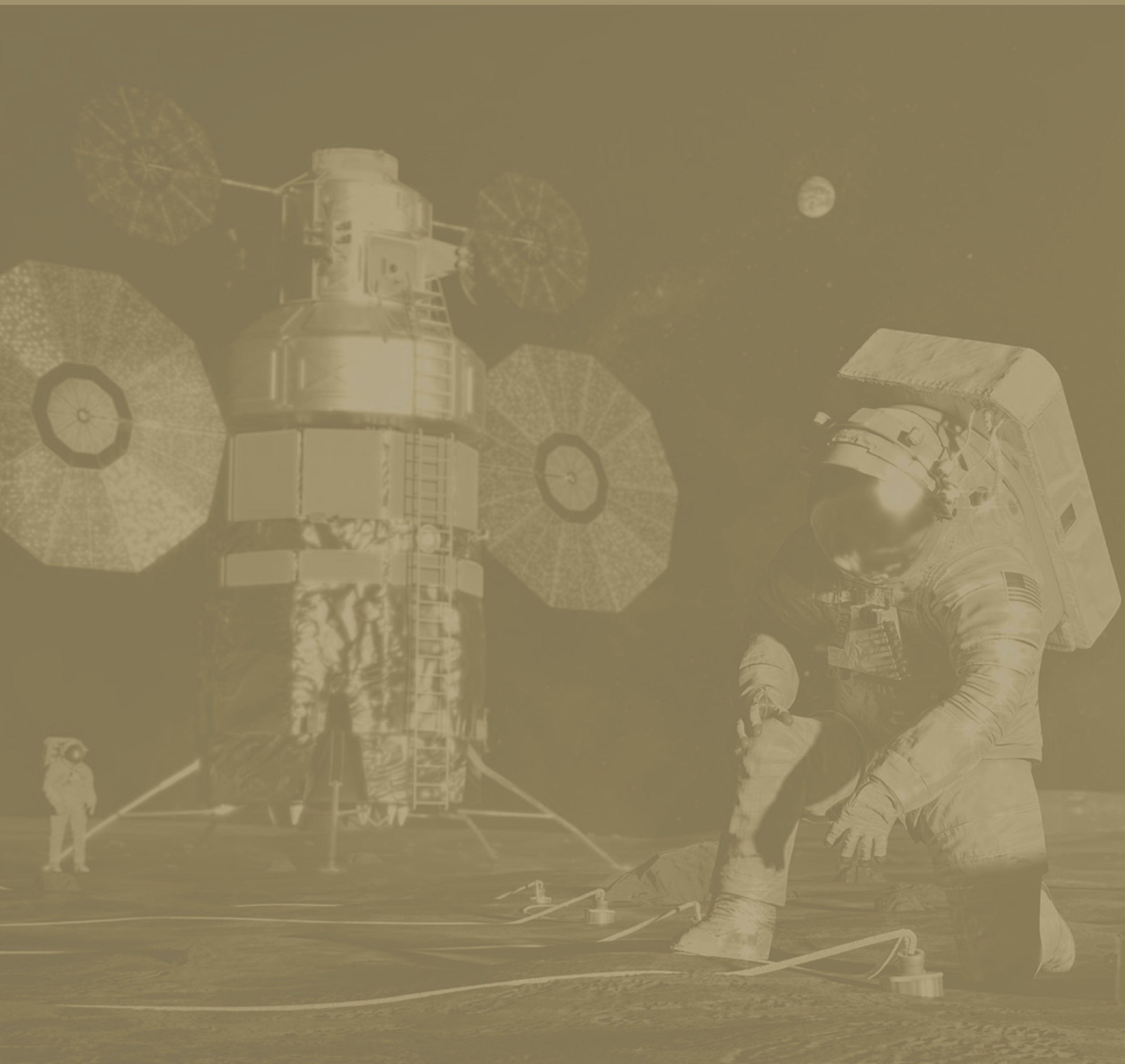
PRINCIPAL INVESTIGATORS: John Carr and Les Johnson

PARTNERS: NeXolve Holding, LLC

FUNDING ORGANIZATION: Space Technology Mission Directorate

TECHNOLOGY AREA 05:

Communications, Navigation, and Orbital Debris Tracking/Characterization Systems



Imaging X-ray Polarimetry Explorer (IXPE)

OBJECTIVE: *To perform x-ray polarimetric imaging of cosmic sources for the first time, adding polarization degree and orientation to the properties (time, energy, and position) observed in x-ray astronomy. In doing so, the Imaging X-ray Polarimetry Explorer (IXPE) will extend the understanding of x-ray sources and processes for various types of neutron stars, stellar-mass black holes, supernovae remnants (SNR), and active galactic nuclei (AGN).*

PROJECT GOAL/DESCRIPTION

Led by NASA MSFC Principal Investigator, Martin C. Weisskopf, IXPE is a NASA Small Explorer (SMEX) mission, in partnership with the Italian space agency (ASI) and with prime contractor Ball Aerospace. The IXPE Observatory will launch in late 2021 into an equatorial, 600-km circular orbit. Following a 1-month orbital commissioning, IXPE will begin its 2-year baseline mission to measure the x-ray polarization of several dozen cosmic sources. IXPE includes three identical x-ray telescopes, each comprising a nested grazing-incidence mirror module assembly (MMA) and a polarization-sensitive (imaging) detector unit (DU), separated by a deployable boom to establish the telescopes' 4-m focal length. The IXPE Observatory includes the telescopes and the spacecraft, which provide typical subsystems—mechanical, structural, thermal, power, electrical, telecommunications, aspect determination and control, and command and data handling.

The Observatory will transmit data to the primary (Malindi, Kenya) or secondary (Singapore) ground station, to be relayed to the Mission Operations Center (Boulder, Colorado) and then to the Science Operations Center (Huntsville, Alabama). All scientific data will be publicly available through NASA's High-Energy Astrophysics Science Archive Research Center (HEASARC) at NASA Goddard Space Flight Center (GSFC). If approved by NASA, the IXPE mission will continue beyond 25 months, initiating a HEASARC-administered general observer (GO) program.

APPROACH/INNOVATION

The enabling technological innovation for IXPE is the polarization-sensitive gas pixel detector (GPD), developed by the Italian Instrument Team. This device images the ionization track of the photoelectron ejected during absorption of an x-ray photon in a gas by drifting the track onto a pixelated application specific integrated circuit (ASIC) after amplifying it with a gas electron multiplier (GEM). Each ionization track contains information on the photoelectron's energy, absorption location, and initial ejection direction, which is correlated with the polarization orientation.

RESULTS/ACCOMPLISHMENTS

There were significant accomplishments in all elements of the IXPE project in 2020. Regarding the IXPE Observatory subsystems, the telescope components (DUs and MMAs,) were completed, tested, and calibrated in Italy and at MSFC, respectively; the boom was successfully deployed at Ball Aerospace. Ball also completed the spacecraft and the installation and alignment of the DUs and MMAs and is preparing for assembly, integration, and testing (AI&T) of the Observatory. The ground system is undergoing integration tests for the network and is preparing for radio-frequency (RF) compatibility tests with the Malindi and Singapore ground stations. The launch vehicle has completed mission specific reviews—including preliminary

FIGURE 1. An artist's representation of IXPE in Earth Orbit.

design review (PDR) and critical design review (CDR)—and the Payload Processing Facility has been selected. Finally, the IXPE project successfully completed the major milestone reviews of system integration review (SIR) and key decision point-D (KDP-D).

The unexpected challenge in 2020 was the COVID-19 pandemic. As an international project, the IXPE team has members in Italy, Japan, and throughout the United States. The difficulties have not been so much technical as logistical—e.g., how to ship the hardware from Point A to Point B during lockdown and how to remotely supervise and monitor handling and testing of the DUs and MMAs at Ball. Through teamwork, all the flight hardware is now at Ball Aerospace in Boulder, Colorado, and the IXPE Observatory is starting AI&T activities.

SUMMARY

In early 2021, the IXPE Observatory will undergo the environmental test program with Mission Rehearsals in Summer 2021. Upon completion and after a successful Operations Readiness Review, the IXPE Observatory will be shipped to Kennedy Space Center (KSC) for launch on a SpaceX Falcon9, from LC-39A in late 2021. By the end of 2021 or early 2022, IXPE data will start to become available to astrophysicists around the world and initial results will give insight into NASA's Astrophysics first objective: *"Discover how the Universe works."* completed cases are projected to occur in January 2021. These tests will take place in the Propulsion Research Laboratory at MSFC with the Advanced Propulsion Branch administering the test.

PRINCIPAL INVESTIGATOR: Martin Weisskopf

PARTNERS: Agenzia Spaziale Italiana (ASI), Istituto di Astrofisica e Planetologia Spaziali / Istituto Nazionale di Astrofisica (IAPS/INAF), Istituto Nazionale Fisica Nucleare (INFN), OHB-Italia, Ball Aerospace & Technologies Corp., University of Colorado, Boulder's Laboratory for Atmospheric and Space Physics (LASP), Nagoya University, Università Roma Tre, Stanford University, Massachusetts Institute of Technology (MIT)

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://www.msfc.nasa.gov/

Smart Video Guidance Sensor (SVGS): A Versatile, Relative Pose Sensor for Cross-Cutting Applications

OBJECTIVE: *To create a space-qualifiable, cross-cutting sensor that is applicable in the domains of rendezvous, proximity operations, and docking; entry, descent, and landing; and lunar surface navigation.*

PROJECT GOAL/DESCRIPTION

The Smart Video Guidance Sensor (SVGS) is a camera-based, relative position and orientation sensor. It comprises two subsystems: a camera subsystem and a target subsystem. The target is made up of retroreflective or LED markers in a specific configuration that is known to the camera subsystem. The camera images the target, performs some light image processing, and then feeds the image to a photogrammetry engine. Since the target configuration is known, photogrammetry can be used to produce the relative position to the target as well as the relative orientation between the two systems. A camera-based vision sensor is applicable to a variety of use cases, including rendezvous, proximity operations, and docking (RPOD); entry, descent, and landing (EDL); and lunar surface navigation. The innovation in SVGS is its small form factor, low weight, and low power draw, enabling SVGS to be applied to resource-constrained platforms such small satellites and commercial landers, as well as larger human exploration and operation-class missions.

SVGS draws on a long history of MSFC-developed technology with flight heritage, including the Video Guidance Sensor (VGS) and the Advanced Video Guidance Sensor (AVGS). SVGS is the next-generation evolution of both these technologies. The goal of the SVGS project is to create a space-qualifiable sensor, achieving technology readiness level (TRL) 6 no later than 2023, with a goal for a flight demonstration in the late 2020s.

APPROACH/INNOVATION

SVGS leverages developments in the commercial industry, particularly those in field programmable gate arrays (FPGAs) and complimentary metal-oxide-semiconductor (CMOS) imagers, to achieve an order of magnitude reduction in form factor and power consumption over its VGS and AVGS predecessors. The key milestones during this year in technology development were:

- Selection of the hardware architecture for finalized design, including processor and CMOS imager.
- Hardware solutions to increase the robustness of the relative pose solution, including sensitivity studies on camera exposure and incorporating bandpass filters in the hardware design tuned to the wavelength of the marker illumination source.
- Demonstration of >10 Hz solution rate on a bread-boarded SVGS concept.

Follow-on funding was secured for FY 2021–FY 2022 through the Space Technology Mission Directorate (STMD) Game Changing Development to design a processor board and enclosure, as well as environmentally test a prototype, with the goal to raise the TRL to TRL 6 by end of FY 2022.

RESULTS/ACCOMPLISHMENTS

In FY 2020, internal research and development funding allowed the SVGS technology to progress to TRL 4. The core SVGS algorithm was implemented in C, while maintaining American National Standards Institute (ANSI) C compliance. This enabled the SVGS algorithm to be ported to any platform with an ANSI C-compliant toolchain. The Xilinx MPSoC FPGA platform was assessed and ultimately selected as the main processor for the finalized version of

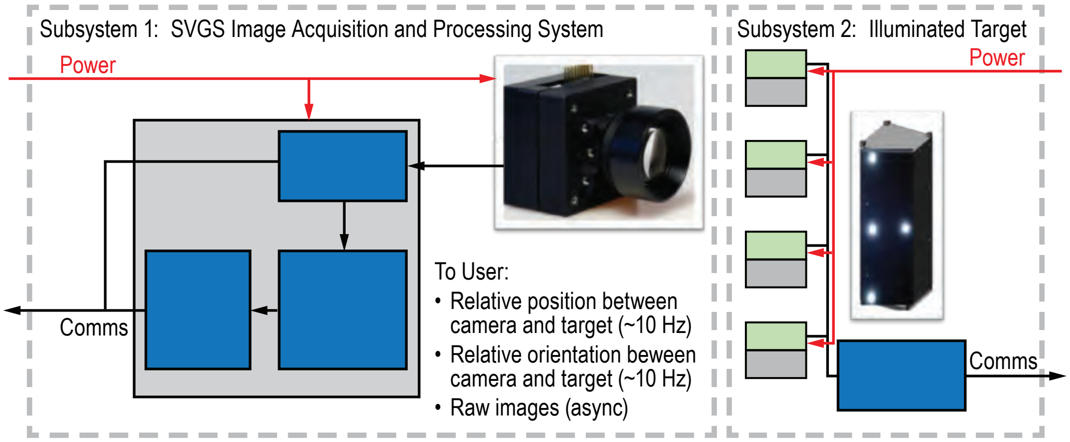


FIGURE 1. Functional block diagram of the SVGS camera (left) and target (right) subsystems. The camera images the target to provide a 6 Degree-of-Freedom solution of the relative position between the two systems.

SVGS due to its unique safety features, fast computational speed, and configurable power consumption. A bread-boarded concept with a commercial CMOS imager was designed, proving the feasibility of the hardware architecture. The SVGS bread-boarded concept was capable of producing relative pose solution rates at greater than 10 Hz, which was limited primarily by the frame rate of the camera.

In a parallel effort, a Space Act Agreement was signed with the developers' partners at Florida Institute of Technology (FIT) and Jaycon Systems that will bring the SVGS technology to the International Space Station. The SVGS software is being implemented on the Astrobee platform, a 6 Degree-of-Freedom (DoF) robotic vehicle onboard the ISS. Multiple Astrobee vehicles are slated to perform RPOD experiments no later than FY 2023, using SVGS as the main relative pose sensor. Additionally, Lake Superior State University and South Dakota School of Mines are exploring utilizing SVGS on mobile robotic platforms for both terrestrial and lunar applications. A final application is being explored in precision landing by FIT with the use of an unmanned aerial system (UAS).

SUMMARY

The continued development path of SVGS during this fiscal year has demonstrated the cross-cutting nature of the technology with applications in RPOD, EDL, and surface navigation. Through partnerships with both industry in academia, SVGS technology has been implemented on UAS and mobile robotic platforms, with an anticipated intravehicular demonstration of the technology utilizing multiple Astrobees on ISS by FY 2023. Design of a space-qualifiable version of SVGS has progressed with a proposed hardware selection and feasibility study proving the validity of the design.

PRINCIPAL INVESTIGATOR: Ivan Rodrigues Bertaska
PARTNERS: Florida Institute of Technology, Jaycon Systems
FUNDING ORGANIZATION: Technology Investment Plan

Velocity-Sensing Light Detection and Range (LiDAR) Scanning System

OBJECTIVE: *To develop a velocity-sensing light detection and range (LiDAR) vision system for 3D navigation and terrain mapping in GPS-denied environments for planetary surface exploration.*

PPROJECT GOAL/DESCRIPTION

Future exploration of the lunar South Pole by rovers and humans will require ways to accurately navigate and map the terrain in challenging solar illumination conditions and in a GPS-denied environment. Three-dimensional scene reconstruction of the topography is needed for navigating and exploring via rover, avoiding hazards, providing scientific context, and creating virtual-reality immersive worlds for public engagement. This project uses nascent frequency modulated continuous wave (FMCW)-LiDAR scanning technology, developed for the self-driving automotive industry, to build a prototype person- or rover-mounted 3D terrain mapping system—the Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR System. The novel use of FMCW-LiDAR sensors, which provide instantaneous velocity measurements for every range data point (>10^6 points/s, ≈cm/s V resolution, <300-m range resolution) and are immune to direct solar illumination, will advance the state-of-the-art in sensing techniques for planetary exploration. This project is developing the prototype hardware and novel position-from-velocity solutions and simultaneous localization and mapping (SLAM) algorithms that make use of integrated velocity and range sensing capabilities and enable GPS-denied operation. Environmental testing to advance chip-scale FMCW-LiDAR technology readiness level (TRL) for lunar and planetary surface exploration is also part of this effort. This project is funded by the NASA Space Technology Mission Directorate (STMD) Early Career Initiative (ECI) program and the MSFC Technology Investment Program (TIP).

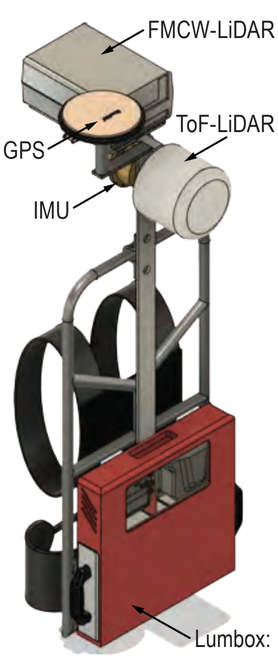


FIGURE 1. The Kinematic Navigation and Cartography Knapsack (KNaCK), a velocity sensing FMCW-LiDAR scanning system for terrain mapping and navigation.

APPROACH/INNOVATION

As an early career initiative project, the KNaCK LiDAR System is a 2-year investigation to develop a state-of-the-art technology that also uses innovative project management strategies and is done in partnership with an industry collaborator and with a NASA team comprised solely of early career civil servants. We use hybrid Agile scrum-ban for project management which provides flexibility for both hardware and software development. We have partnered with Torch Technologies, a Huntsville-headquartered engineering firm with expertise in photonics engineering and is Agile PM certified. The technology is a backpack-mounted mobile 3D scanning system, comprised of both an FMCW-LiDAR sensor and a traditional time-of-flight LiDAR sensor, an inertial measurement unit, and GPS hardware. Combined, these subsystems create a tightly coupled inertial navigation system with real-time 3D point-cloud data collection and high-definition video capture. GPS data are collected primarily as control for algorithm testing. The choice to develop a backpack-mounted system is intentional, as it is inherently portable and more rapidly deployed in GPS-denied testing environments

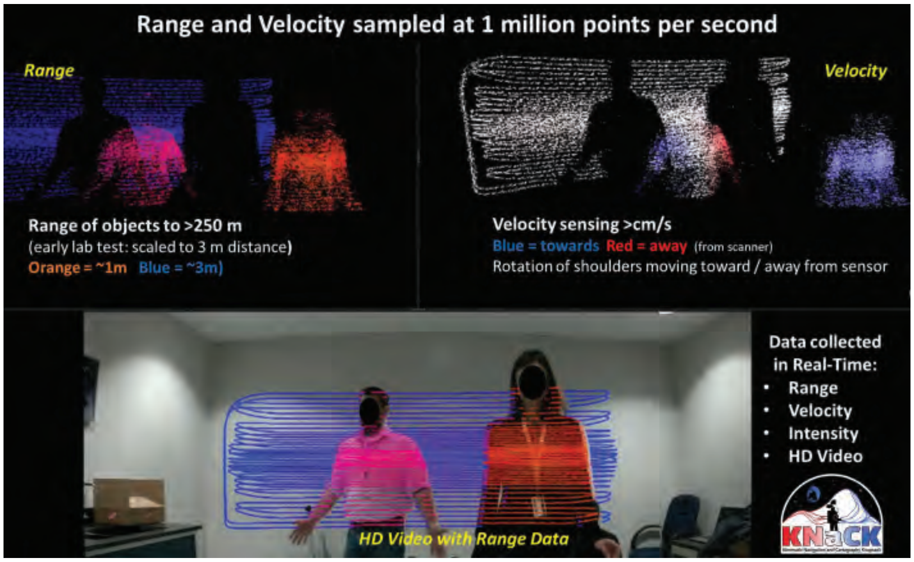


FIGURE 2. Laboratory data demonstration of range and velocity sensing capabilities of a commercially procured prototype FMCW-LiDAR sensor developed for the self-driving automotive industry.

compared to unmanned aerial vehicles (UAVs) or rovers. The backpack configuration also allows the KNaCK system to be used as a science instrument for topographic data collection for geology and geomorphology.

The project objects are to:

(1) Build a GPS-enabled KNaCK prototype mobile FMCW-LiDAR scanning system.

(2) Develop GPS-Denied mobile LiDAR.

(3) Develop the FMCW-LiDAR sensor for space.

A major innovation of the KNaCK LiDAR system is the development of use-cases for FMCW-LiDAR sensors for range finding, navigation, and terrain mapping in planetary exploration. FMCW-LiDAR is an emerging, chip-scale sensor technology developed for the self-driving automotive industry. Operating with a steered linearly chirped (frequency modulation) continuous wave (coherent laser) beam allows for the measurement of the Doppler shift of a returned signal, providing velocity data for every point in a wide field of view. The concomitant collection of range and velocity from a single sensor essentially provides real-time odometry in one sensor, eliminating the need for wheel sensors. Additionally, the combination of velocity and range allows for the solution of the scanner position in a static scene, which can then be integrated with IMU orientation data, constraining bias error drift and resulting in a novel SLAM algorithm solution and favorable for GPS-denied operation. On the KNaCK backpack platform the development of these algorithms is aided by subtle motions from walking, which provides more positioning feedback than other locomotion methods. Additional use-cases for these sensors are being investigated as part of this project, including rover-mounted autonomous navigation and hazard avoidance and in field testing of spacecraft landing simulations via a crane-mounted sensor breadboard.

RESULTS/ACCOMPLISHMENTS

A full-system, integrated KNaCK breadboard is complete and is in frequent use for data collection to aid SLAM navigation algorithm development, exceeding schedule despite pandemic response constraints. A full backpack prototype is anticipated in November 2020. A recent use-case investigation successfully simulated spacecraft landing simulations via a crane-mounted system breadboard. Algorithm development is on schedule, and environmental testing of sensor components for space use will begin in the coming year. The project has allowed for collaboration projects with NASA Johnson Space Center (JSC) and Ames Research Center (ARC), as well as involving additional branches within MSFC. The project has also incorporated academic research, supporting a MFSC Faculty Fellowship over the summer that continues on, as well as supporting undergraduate Capstone senior design teams at Texas A&M and the University of Alabama in Huntsville in expanding the use cases for this technology.

SUMMARY

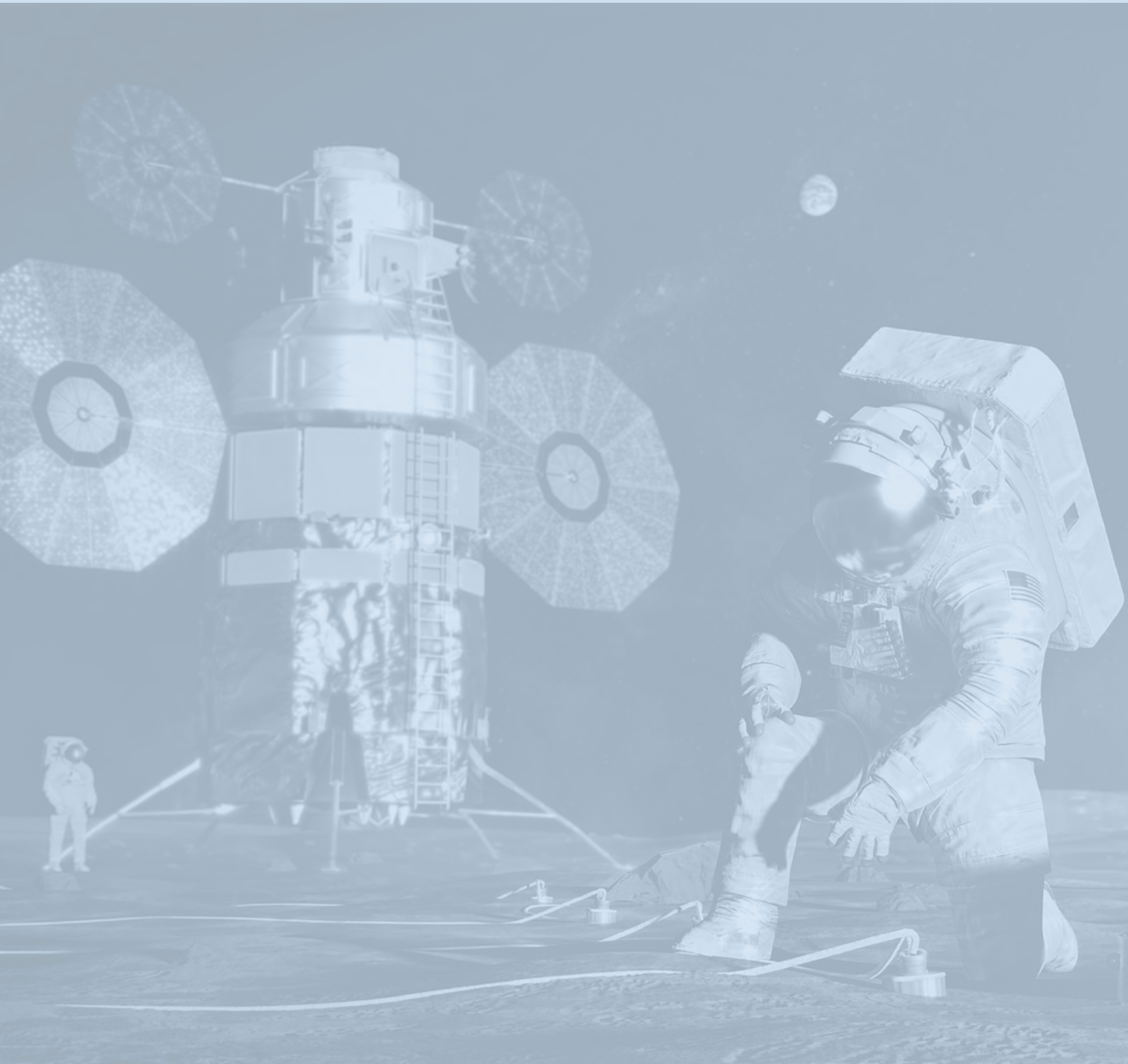
The KNaCK LiDAR system ECI project is rapidly advancing the use of FMCW-LiDAR technology for terrain mapping and navigation for planetary exploration. Promising results for GPS-denied navigation through sensor data fusion and position-solution algorithms have been achieved. Future work will focus on environmental testing of sensors for space-use.

PRINCIPAL INVESTIGATOR: Michael Zanetti

PARTNERS: Torch Technologies

FUNDING ORGANIZATIONS: Space Technology Mission Directorate, Technology Investment Plan

TECHNOLOGY AREA 06:
Human Health, Life Support, and Habitation Systems



Paramagnetic Ionic Liquids for Enhanced Gas Absorption

OBJECTIVE: *To develop hardware for a parabolic flight experiment that will demonstrate the spatial control of paramagnetic ionic liquid aerosols in microgravity using applied magnetic fields.*

PROJECT GOAL/DESCRIPTION

The technology currently used on the International Space Station to remove carbon dioxide (CO_2) from the cabin air is not capable of meeting the new, lower CO_2 exposure limits for long-duration spaceflight. This has necessitated further developments in CO_2 capture technology, with much of this work being done to investigate new sorbent materials. One particularly promising class of sorbents are ionic liquids (ILs), which can be designed to have high CO_2 capacity, along with extremely low vapor pressures and high stability. The challenge with using IL sorbents stems from their high viscosity, which inhibits the rate at which CO_2 can diffuse into the bulk material. One solution to this is to maximize the surface area to volume ratio of the IL, which can be accomplished by creating a two-phase system of cabin air and a liquid sorbent aerosol. Separating such a two-phase flow is trivial on Earth due to gravity-driven separation but remains challenging in microgravity. The goal of this project is to demonstrate that applied magnetic fields can be used in lieu of gravity to separate paramagnetic ionic liquids (PILs) from air.

APPROACH/INNOVATION

The technology being developed as part of this effort contains two major innovations: the use of applied magnetic fields on PILs in lieu of gravity to promote two-phase separation and the synthesis of an IL that is both paramagnetic and has a high affinity for CO_2. Prior work demonstrated that magnetic control of PILs is possible, and this project seeks to build on that by designing and fabricating the hardware necessary for a microgravity experiment on a parabolic flight.

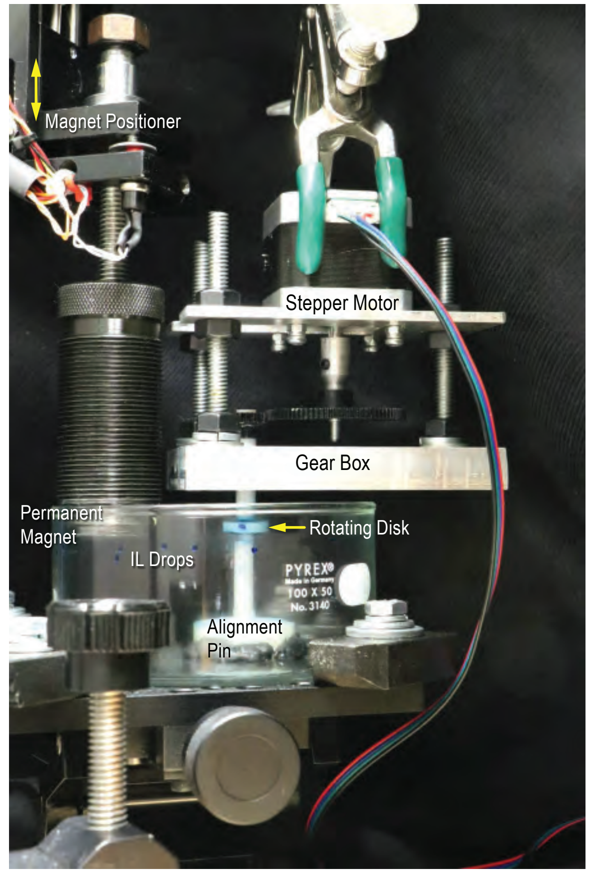


FIGURE 1. Experimental hardware.

ACCOMPLISHMENTS

The most challenging part of the microgravity experiment is reliably producing single drops of PIL that are then directed through a magnetic field, while also preventing any release of PIL due to fluctuations in gravity during parabolic flight. To overcome this challenge, a novel piece of hardware that uses a spinning Teflon™ disk to produce single drops of PIL was designed and built. Additionally, the ability of the IL reservoir to contain the PIL between zero and two gravities was demonstrated using an oscillating

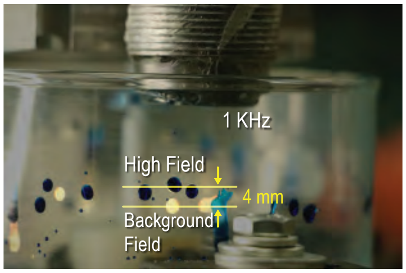


FIGURE 2. Deflection of PIL droplets in a magnetic field (high field) compared to droplets in no magnetic field (background field).

beam device. Finally, the ability of the hardware to deflect PIL drops using an applied magnetic field was verified.

Limited access to the laboratory during the year precluded the synthesis of a CO_2-absorbing PIL. However, a review of the literature on PILs identified new paramagnetic functionalities for ILs are based on holmium. These PILs exhibit twice the magnetic moment of the PILs currently used than previously used. As the applied force on a PIL scales linearly with the magnetic moment, these new PILs should exhibit a much greater response when exposed to a magnetic field. A functional group to promote CO_2 sorption, tertiary amines, was identified, and a synthesis route to prepare PILs containing holmium-based anions and tertiary amines was developed.

SUMMARY

The use of applied magnetic fields and PILs is an intriguing route to allow for the separation of multiphase systems in microgravity, which has potentially valuable applications for CO_2 capture in life support processes for long duration, deep space missions. This study developed and qualified the necessary hardware for a parabolic flight experiment to allow for proof-of-concept of this innovative technology to be accomplished via parabolic flight experiments. Future work will focus on the synthesis on the synthesis of a PIL that is also a CO_2 sorbent and a flight experiment using the fabricated hardware.

PRINCIPAL INVESTIGATORS: Eric T. Fox (MSFC), Matthew J. Marone (JSEG)

FUNDING ORGANIZATION: Technology Investment Plan

Electrolytic Oxygen Recovery for ECLSS

OBJECTIVE: *To develop a macrofluidic electrochemical reactor to achieve an oxygen recovery efficiency of the process to greater than 50% and to scale up the system hardware to achieve a one crew member carbon dioxide conversion rate.*

PROJECT GOAL/DESCRIPTION

The state-of-art (SOA) Environmental Control and Life Support System (ECLSS) oxygen recovery system is only capable of recovering approximately 50% of the oxygen (O_2) from metabolic carbon dioxide (CO_2). Investigations into various technologies to help increase the oxygen recovery rate for future human exploration missions are ongoing; however, most of these proposed technologies are complex, heavy, and power consuming. The development of an electrolytic oxygen recovery system is a collaborative effort between NASA MSFC with the University of Texas Arlington (UTA) and has the potential to significantly reduce the complexity of the ECLSS O_2 recovery system. This system will utilize a macrofluidic electrochemical reactor (MFECR) which converts O_2 and water (H_2O) into O_2 and ethylene (C_2H_4) using H_2O as a proton source and has a theoretical O_2 recovery rate of 73%. The MFECR operates at standard conditions, giving it an advantage over other O_2 recovery technologies being investigated. Most O_2 recovery technologies require high operating temperatures, which results in heavy, high power-consuming reactors. Another advantage of the MFECR is the ability to produce O_2 in a single gas channel. The SOA and other technologies investigated for O_2 recovery require a post process in which the H_2O product is electrolyzed by the Oxygen Generation Assembly (OGA) to generate O_2. This system would significantly reduce the complexity of ECLSS by allowing for one piece of hardware for O_2 recovery versus the three pieces of hardware currently required in the baseline exploration O_2 recovery architecture. To date, this technology has demonstrated a CO_2 recovery rate of 37%. Current efforts are focused on further development of the MFECR to achieve a metabolic CO_2 recovery rate of greater than 50% and scaling up the system hardware to achieve a one crew member conversion rate.

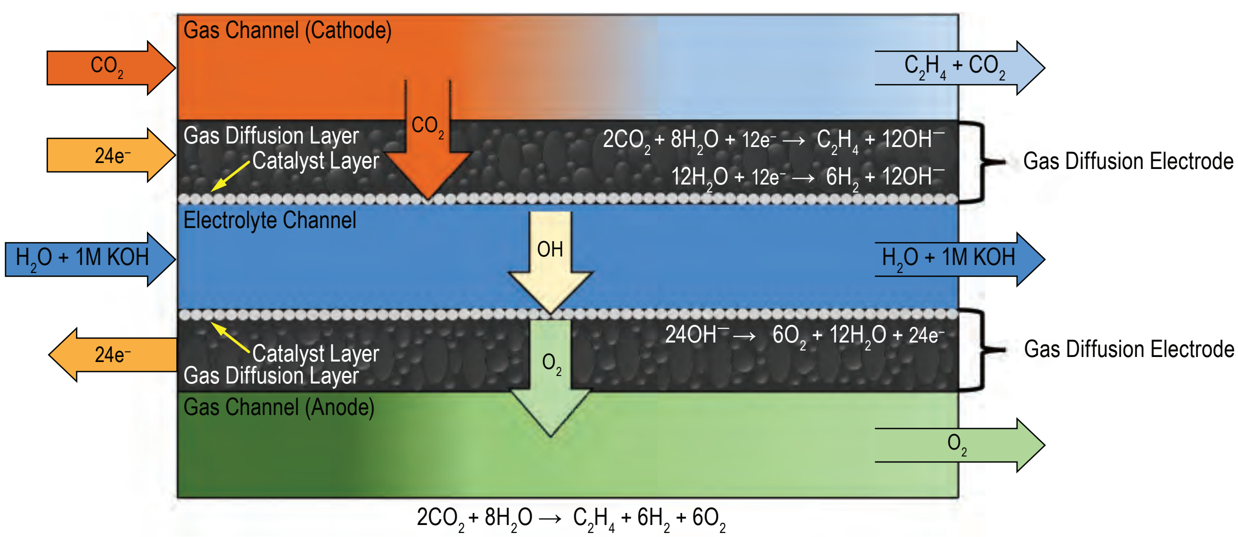


FIGURE 1. Cross section of a single cell MFECR.

APPROACH/INNOVATION

In the MFECR design shown in figure 1, a gas diffusion electrode (GDE) separates the anode and cathode gas channels from the electrolyte channel. The GDE surfaces have an electrodeposited layer of nanocomposite particles that act as electrocatalysts for the reaction on the anode and cathode. The electrolyte used is a potassium hydroxide (KOH) H_2O mixture. To complete the reaction, an electrical potential is applied across the electrodes, O_2 is produced when the H_2O in the electrolyte is consumed at the anode, and the protons that are produced react with CO_2 on the cathode. To maintain H_2O volume, H_2O may be occasionally added from the Water Processing Assembly. KOH is not consumed through the process and therefore does not have to be replaced. To achieve higher metabolic CO_2 conversion rate, current efforts have been focused on the following areas: optimization of the cell design, anode material development, and cathode catalyst development.

RESULTS/ACCOMPLISHMENTS

To increase the O_2 recovery rate, modifications were made to the original MFECR Engineering Design Unit (EDU). Successful fabrication of serpentine electrodes will allow for an increase surface area resulting in higher CO_2 reduction. Alternative materials for the cell's electrical current distributor and electrolyte walls were chosen to avoid degradation due to oxidation. A nonconductive material was chosen for the pressing plates and an alkaline-tolerant material was chosen for the electrolyte walls. Nickel foam material has been selected as an alternative anode material. Due to the corrosive properties of the KOH electrolyte, alternative electrolyte solutions, such as sodium bicarbonate and ionic liquids, have been explored. To date, no alternative electrolyte to KOH has been selected due to low performance. However, some ionic liquids still under investigation appear promising. The design and fabrication of the EDU test stand is complete. The test stand, shown in figure 2, is fully automated and contains all the necessary components to complete testing of the EDU. The EDU will be equipped with all the instrumentation and sensors that will allow for full validation of a rigorous multiphysic 3D model that has been developed. The model includes all the physics involved in the MFECR process such as electrochemical physics, microfluid flow, mass and heat transfer, generation, and conduction of direct current (DC) electrical current, and will provide the capability to optimize the cell design and operation of the EDU.

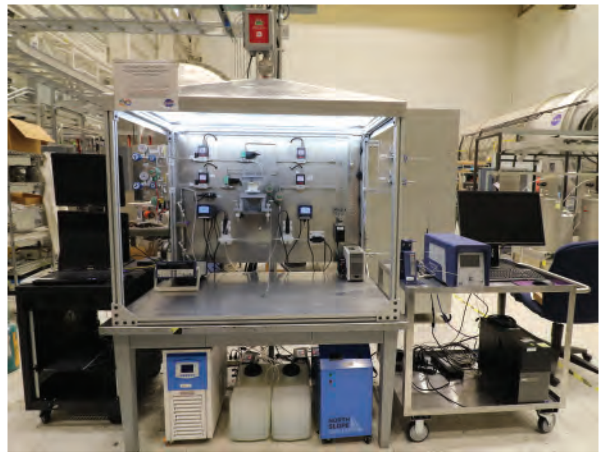


FIGURE 2. Electrolytic oxygen recovery test stand.

SUMMARY

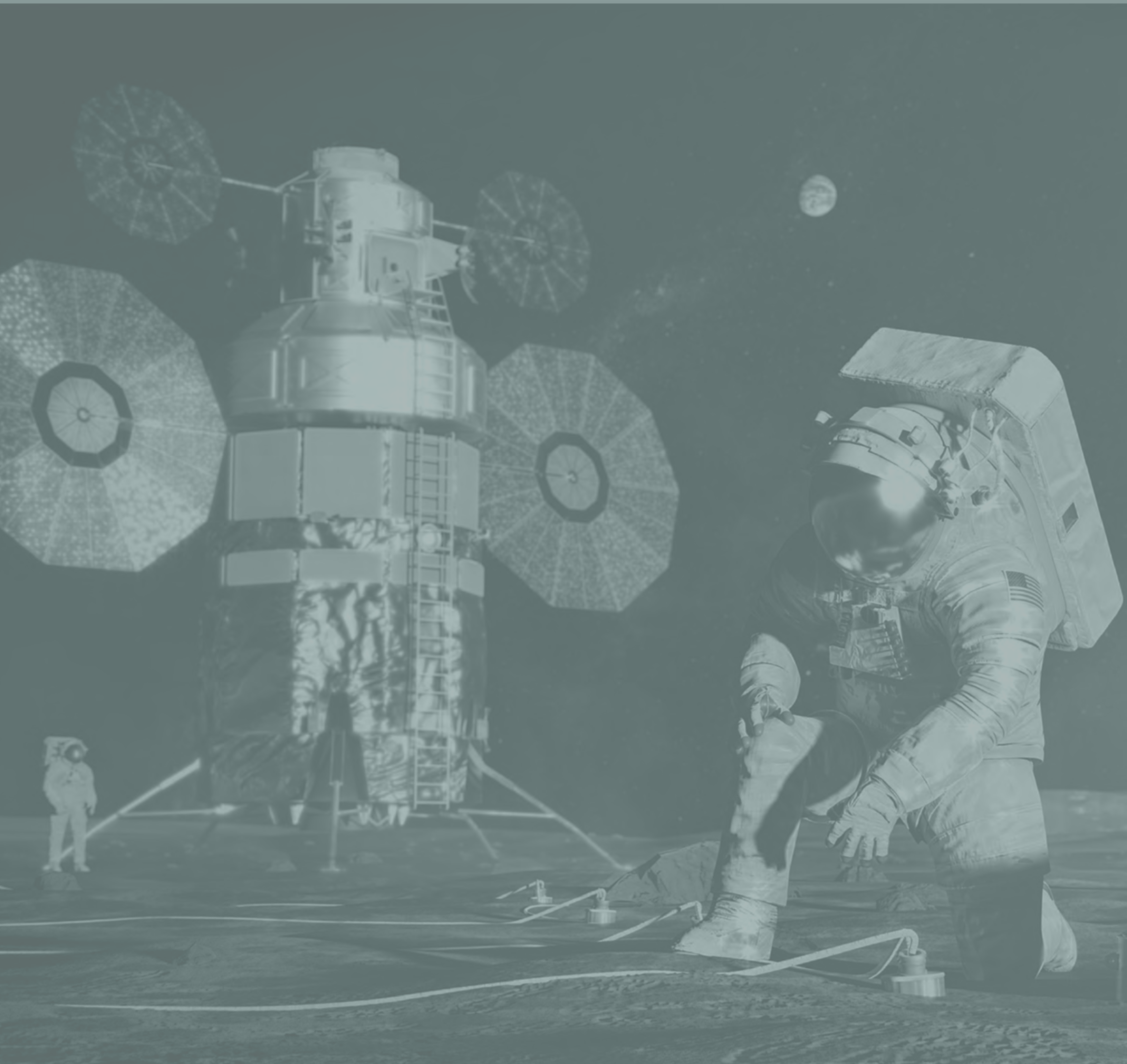
An electrolytic O_2 recovery system is highly attractable technology for future long duration missions due to the ability of decreasing the complexity and increasing reliability of ECLSS. This system converts CO_2 and H_2O into O_2 and C_2H_4 using H_2O as a proton source. Efforts have been made to further develop this technology by addressing the key issues identified in the initial developmental effort in order to achieve a metabolic CO_2 recovery rate of greater than 50%. Alternative cell component materials have been chosen in order to address the degradation and conductivity issues. To ensure long-term usage of hardware, alternative electrolyte solutions have been investigated. A fully automated test stand has been fabricated in which the EDU will be tested, and the data will be used to validate the multiphysic 3D model in order to optimize cell design and operation of the system

PRINCIPAL INVESTIGATOR: Brittany Brown

PARTNERS: University of Texas Arlington

FUNDING ORGANIZATION: Technical Excellence

TECHNOLOGY AREA 07:
Exploration Destination Systems



Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project

OBJECTIVE: *To develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure elements on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms, and blast shields using lunar regolith-based materials.*

PROJECT GOAL/DESCRIPTION

NASA needs the capability to consolidate and stabilize regolith on large scales, including microwaves and additive manufacturing-based construction or additive construction (AC) (NASA Technology Taxonomy (TX)07.2.3) to mitigate dust (TX13.4.5) via in-situ manufacturing and repair (TX07.2.2) to sustain a long-term human presence on and utilize the Moon (NSP Objective 2.2). The same capability provides a thermal heater for volatile extraction from regolith (TX07.1.3, microwave), a heating source (TX14.2.6, microwave), and ultimately radiation protection structures for habitats (TX12.1.4, microwave and AC). This capability currently does not exist.

APPROACH/INNOVATION

The Lunar Surface Innovation Initiative (LSII) Formulation Planning Guidance for Lunar Construction identified the following capability needs addressed within the MMPACT Project.

- Material and construction requirements and standards: MMPACT is partnered with Space Exploration Architecture (SEArch+, the 3D-Printed Habitat Challenge Design Award Winner in 2 Phases), Bjarke Ingels Group (BIG), ICON Technology, Inc., and other members of industry and academia to support construction requirements and standards development. Additionally, MMPACT partnered with materials experts within NASA, industry, and academia to support material requirements and standards development.
- Increased autonomy of operation: MMPACT is partnering with the Defense Innovation Unit (DIU), the Air Force Civil Engineering Center (AFCEC), the Texas Air National Guard (TANG) and ICON (who is building the only permitted, seismic-compliant housing in the U.S. and Mexico using AC) to increase autonomy of operations and remote operations capabilities for construction systems.
- Scale of construction activities: MMPACT is leveraging current technology elements at ICON and MSFC, as well as maturing microwave processing protocols and thermal design to technology readiness level 6. The team plans for early demonstrations of subscale planar construction capabilities in printing of a Lucy Student Pipeline Accelerator and Competency Enabler (L'SPACE) student team-designed landing pad. The team will also develop lunar Job Site Mobility Systems (JSMs) and Materials Deposition System (MDS) prototypes. The team is targeting a lunar surface technology demonstration in 2025 for MDS proof of concept on a Commercial Lunar Payload Services (CLPS) lander.
- Hardware operation and manufacturing under lunar environmental conditions: The MDS and JSM candidates will be evaluated, down-selected, and performance tested in a thermal vacuum (TVAC) chamber. The prototype microwave system will also be TVAC tested. Resulting materials will be characterized for properties used in structural models. This portion of the effort leverages (1) MSFC's expertise and experience in microwave and

FIGURE 1. Illustration of a potential habitat on the south pole of the Moon. Image used with permission from MMPACT partners ICON and the Bjarke Ingels Group (BIG).

FIGURE 2. Potential lunar base design featuring landing pads protected by berms. Image used with permission from MMPACT partners ICON and SEArch+.

additive manufacturing construction materials and technologies, (2) industry advances made from the 3D-Printed Habitat Centennial Challenge, and (3) extensive partnering with the Air Force.

- Long-duration operation of mechanisms and parts: The MMPACT payload will be designed for dust mitigation, leveraging LSII programmatic element linkages/interfaces and a Yet2 Dust Mitigation technology survey. The materials will be selected based on their ability to operate in lunar environmental conditions. The technology will be designed for robustness, robotic field reparability, and assessed for vulnerabilities in the lunar environment.

RESULTS/ACCOMPLISHMENTS

The MMPACT Project received LSII funding in quarter 3 of FY 2020. To date, the team has (1) developed detailed design concepts for lunar habitats, landing pads, and lunar bases (SEArch+ and BIG); (2) developed and tested 100% in-situ resource-based construction materials (ICON); and (3) worked with the L'SPACE team and the MSFC Chief Technologist to print the student-designed landing pad (MSFC, ICON). The team is on track for a flight demonstration in 2025.

PRINCIPAL INVESTIGATOR: Raymond Clinton

PARTNERS: ICON, BIG, SEArch+, Jet Propulsion Laboratory, Kennedy Space Center, Jacobs Space Exploration Group, Blue Origin, Pennsylvania State University, Mississippi State, University of Mississippi, Drake State Community and Technical College, Crown College, University of Nevada in Las Vegas, Holly Shulman, RW Bruce Associates LLC, Microwave Properties North, Radiance Technologies, Southern Research, Southeastern Universities Research Association, JP Gerling, United States Air Force, AFCEC, TANG, DIU, Logical Innovations, Aerie Aerospace, MTS, Space Resource Extraction Technologies, and Microwave Materials Technologies

FUNDING ORGANIZATION: Space Technology Mission Directorate

FOR MORE INFORMATION: https://www.nasa.gov/oem/surfaceconstruction

Resource Recovery with Ionic Liquids for Exploration (RRILE)

OBJECTIVE: *To mature the process of recovering oxygen from lunar regolith using ionic liquids.*

PROJECT GOAL/DESCRIPTION

The Resource Recovery with Ionic Liquids for Exploration (RRILE) project is maturing a novel process that uses ionic liquids (ILs) to extract oxygen from lunar regolith simulant in a proof of concept, lab-scale demonstration that will increase the technology maturation to a technology readiness level (TRL) 3. A closed-loop, continuous system will be developed to chemically digest the regolith and recycle the IL. The project will develop an understanding of the process parameters that will allow the design of a system to meet the oxygen production requirements for a lunar mission.

The project goals are:

- Mature the process of recovering oxygen from regolith using IL.
- Develop a closed-loop, continuous process that will not need resupply of IL.
- Reduce energy needs for oxygen recovery from regolith.
- Understand process parameters that affect the design of future systems including a subscale, surface demonstration system.

APPROACH/INNOVATION

The RRILE project will evaluate commercial and custom ILs based on rate of oxygen generation, effectiveness of digestion of simulant, and regeneration of IL, develop a closed-loop, integrated lab system, perform 6-month stability testing that will evaluate the initial oxygen production rate, the stability of the IL, and oxygen production rate over time.

RESULTS/ACCOMPLISHMENTS

Evaluating and identifying a suitable IL to meet the requirements of the 6-month stability testing was the primary task for FY20. Information gained during this activity will assist with development of the overall system architecture and design of component hardware. Ionic liquids are evaluated based on their efficacy to digest regolith simulant and single-mineral beneficiated regolith simulant, which is a vital step towards the oxygen extraction process, and their ability to be regenerated and recycled for further use.

The project evaluated the efficacy of ILs (1-ethyl-3-methylimidazolium (EMI) hydrogensulfate (HSO_4), betainium bis(trifluoromethanesulfyl)imide (TFSI), taurinium HSO_4, taurinium TFSI, EMI HSO_4, glutamic HSO_4, and tetramethylammonium dihydrogen phosphate)) at digesting JSC-1 lunar regolith simulant. A higher concentration of metals dissolved indicates that more water is produced. The water produced is then electrolyzed to form hydrogen (H) and oxygen (O_2). The hydrogen is then used to regenerate (recycle) the used IL. After regeneration, the IL is reused to digest more regolith. The majority of the metals dissolution was complete in fewer than 5 hr of digestion time, indicating that the regolith digestion reactor

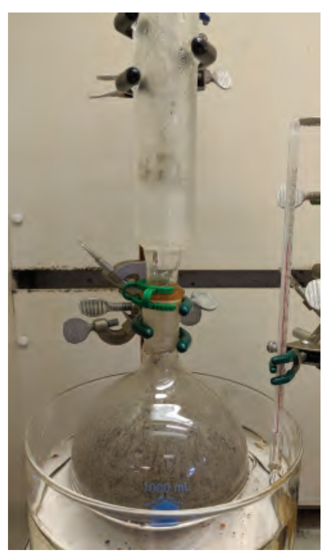


FIGURE 1. Stirred reactor used for evaluating ILs for regolith simulant digestion efficacy.

can have a low residence time. This will decrease the overall volume and mass of the hardware.

The digestion of regolith is significantly enhanced by the addition of a chelating agent (water) as many of the metal salts formed by the process are insoluble in the anhydrous IL. A 2 molar (M) solution of EMI HSO_4 in water was found to offer the maximum extraction of metals, thus production of water. The need to control the water concentration in the system, rather than extract all of the water after the regolith digestion step, will introduce additional hardware complexity but should be possible. Higher concentrations of IL lead to high solution viscosity, particularly for solutions containing dissolved metals, which appears to inhibit the further dissolution of regolith and introduces complications into the regeneration process of the spent ILs. Nonaqueous solvents (e.g. diglyme) appear to also be promising cosolvents for the digestion of regolith. The increased electrochemical stability of such solvents should also make the electrochemical regeneration of the spent ILs easier.

With variations in regolith composition, it is important to develop an understanding of how ILs process the various mineral components of regolith. A review of the literature suggests that certain components (e.g. olivine) will more readily liberate oxygen than others (e.g. feldspar). It may be possible to enhance the performance of the system by having a single mineral input. The project acquired terrestrial analogues of the four most abundant lunar minerals (feldspar, olivine, pyroxene, and ilmenite). Digestion of ilmenite showed that while the extraction of iron was greater relative to the concentration extracted from JSC-1, the overall amount of metals extracted, thus oxygen produced, was lower. Digestion of olivine resulted in approximately twice the total amount of metals extracted compared to JSC-1.

A small-scale electrochemical reactor was designed and fabricated to investigate the regeneration of spent IL and the concurrent electroplating of dissolved metals. Small volume (12 ml) with an adjustable flowrate was fabricated to replicate residence time in final regolith digestion reactor. The first regeneration studies focused on 1 M solutions of EMI HSO_4 IL reacted with nickel. While nickel is not a major component of regolith, it is very similar electrochemically to iron and has the advantage of not oxidizing in an oxygen atmosphere. After the spent IL solution was run through the regeneration cell, a black-colored layer of metal was deposited on the copper electrode, and there was a drop in pH. These are indications that the IL was regenerated. The second set of regeneration studies will focus on dissolving and plating magnesium. As magnesium is the most electropositive of the major metals being extracted from the regolith simulant, it will be the most difficult to electroplate and should prove the most challenging for the regeneration of the IL.

The project also performed preliminary trials with different digestion reactors. A packed bed reactor was selected as the hardware of choice due to its simplistic, robust design. The project will size the hardware to meet performance needs based on data collected during the IL evaluation phase.

SUMMARY

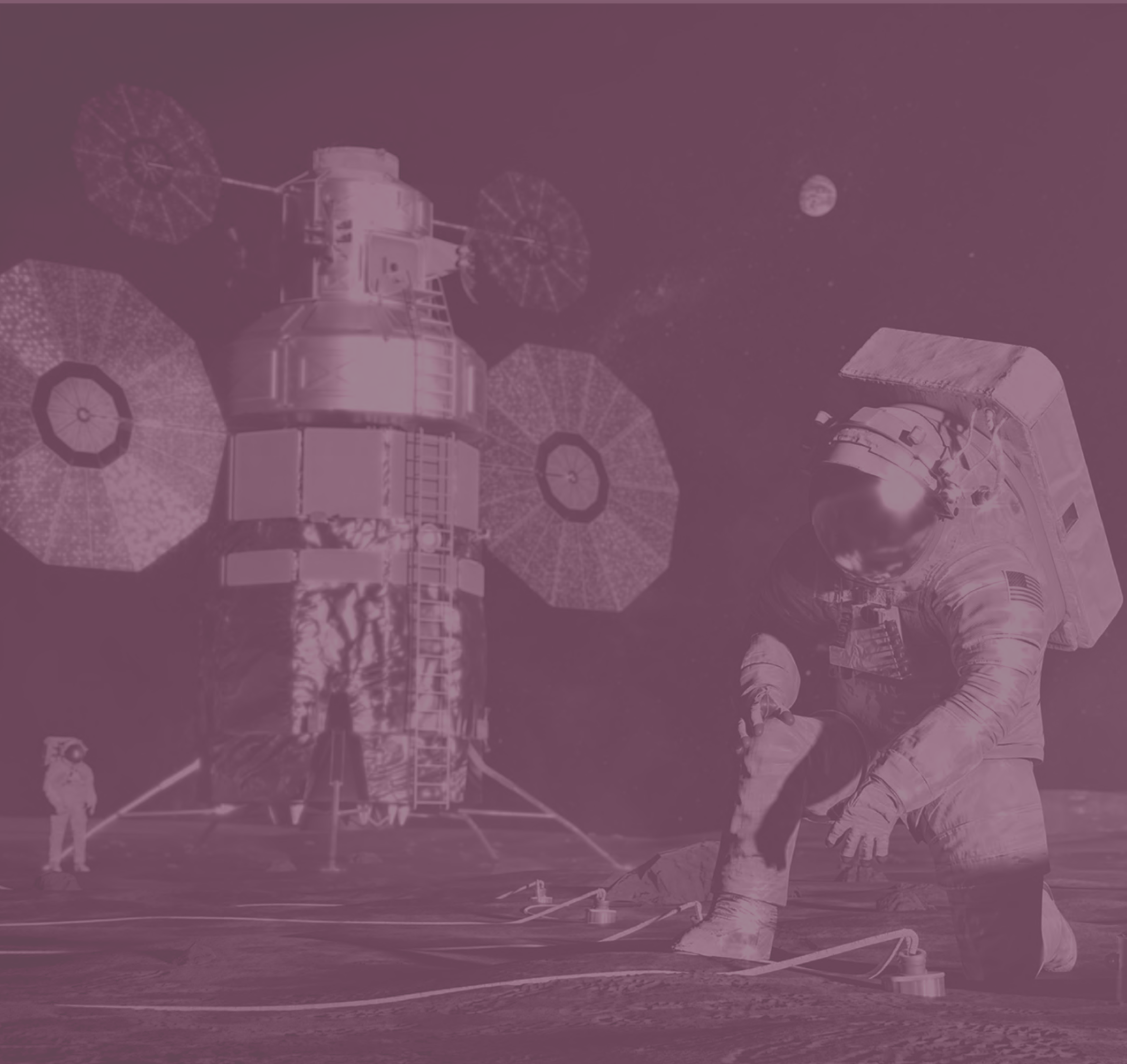
Although FY 2020 was full of surprises, the RRILE project was able to make significant progress towards identifying a usable IL for the 6-month stability testing. The RRILE project was also able to make progress with system design and initial component testing of the packed bed reactor. As the project continues into FY 2021, it will focus on completing the evaluation of ILs, focus on developing the IL regeneration hardware, and integrating and qualifying the system for the 6-month stability testing.

PRINCIPAL INVESTIGATOR: Mallory Johnston

FUNDING ORGANIZATIONS: Space Technology Mission Directorate, Game Changing Development

TECHNOLOGY AREA 08:

Sensors and Instruments



Pulse Shape Discrimination for Gamma-ray Detectors on SmallSats

OBJECTIVE: *To miniaturize gamma-ray detector for SmallSats.*

PROJECT GOAL/DESCRIPTION

Gamma-ray detectors can be made smaller by using a combination of phoswich scintillator and silicon photomultiplier. This combination allows for smaller volume, mass, and power consumption. The goal of the project is to develop read-out electronics that can also perform pulse shape analysis to distinguish forward- versus backward-incident photons, and to veto background events. This will increase the detector sensitivity comparable to current detectors using photomultiplier tubes, allowing SmallSats to achieve science goals done by full-scale missions.

APPROACH/INNOVATION

Phoswich is composed of two different scintillation materials, each with different response time. This timing information can be used to distinguish background noise such as gamma rays coming from the back of the spacecraft. Our phoswich uses thallium-activated sodium iodide NaI(TI) and sodium-doped cesium iodide CsI(Na), which have decay times of 230 and 630 ns, respectively. We are developing a pulse shape discrimination method to demonstrate that the photon direction in the energy range 50–300 keV (prime range for gamma-ray bursts detection) can be distinguished and backward-incident photons can be identified as background, thus increasing the sensitivity of the detector. After lab demonstration, we will have an initial circuit board design using a field-programmable gate array (FPGA), selected for its flexibility in modifying triggering threshold and output. An FPGA prototype will be built, and the logic development for pulse analysis will continue in the lab.

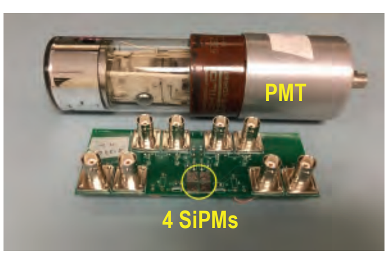


FIGURE 1. A 2-in photomultiplier tube (PMT) and four 6-mm Silicon photomultipliers (SiPM) for size comparison.

For the silicon photomultiplier (SiPM), a commercial off-the-shelf product is used. It does not require high voltage like a photomultiplier tube (PMT) does, and its volume is much smaller. For the SiPMs we have procured, 49 SiPMs cover similar surface area as a 2-in PMT while occupying only 1% of the PMT volume. (See figure 1 for a comparison of one 2-in PMT and four 6-mm SiPMs mounted on a circuit board with BNC connectors.)

While phoswich and SiPM have been flown individually, the combination has not. We plan to follow on with a technology demonstration balloon flight for the hardware and software developed during this project, to be proposed in the upcoming Research Opportunities in Space and Environmental Sciences (ROSES) Astrophysics Research and Analysis solicitation.

RESULTS/ACCOMPLISHMENTS

We have established the optimal waveform to use for the FPGA software, using our custom charge integrated waveform rather than the raw waveform. The detector energy threshold is driven by the CsI(Na) scintillator, the NaI(TI) has a lower threshold. Our pulse shape discrimination method lowered the energy threshold of the CsI(Na) from 40 keV to 15 keV (figure 2) while maintaining the separation power (figure 3) when compared to the commercial (CAEN) pulse shape discrimination solution.

Our lab measurements have provided input to the FPGA design. Currently, we are waiting for prototype design and build to complete. Once that is delivered,

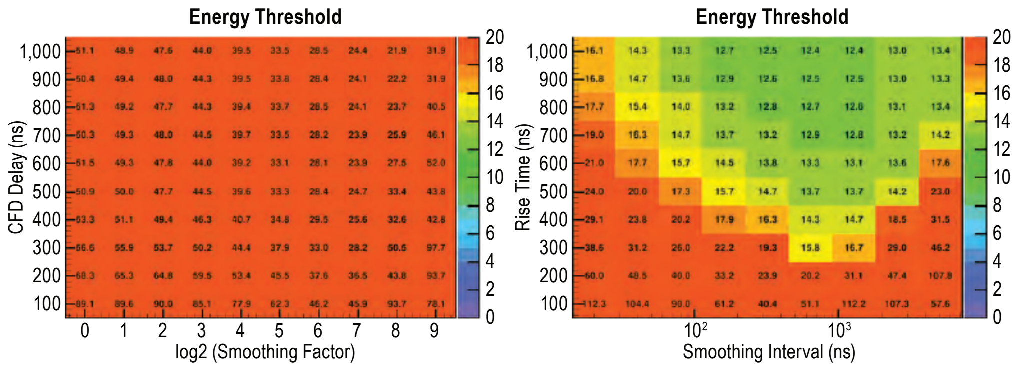


FIGURE 2. (Left) CsI energy threshold using commercial pulse shape discrimination. (Right) CsI energy threshold using our custom solution.

lab testing with the FPGA board will begin to verify performance and further optimize our software.

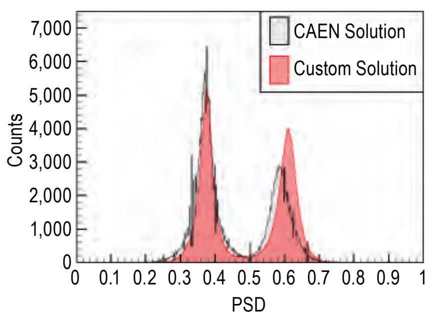


FIGURE 3. Pulse shape discrimination parameter, showcasing the separation of NaI vs CsI pulses. Both commercial and custom solutions have similar separation power.

SUMMARY

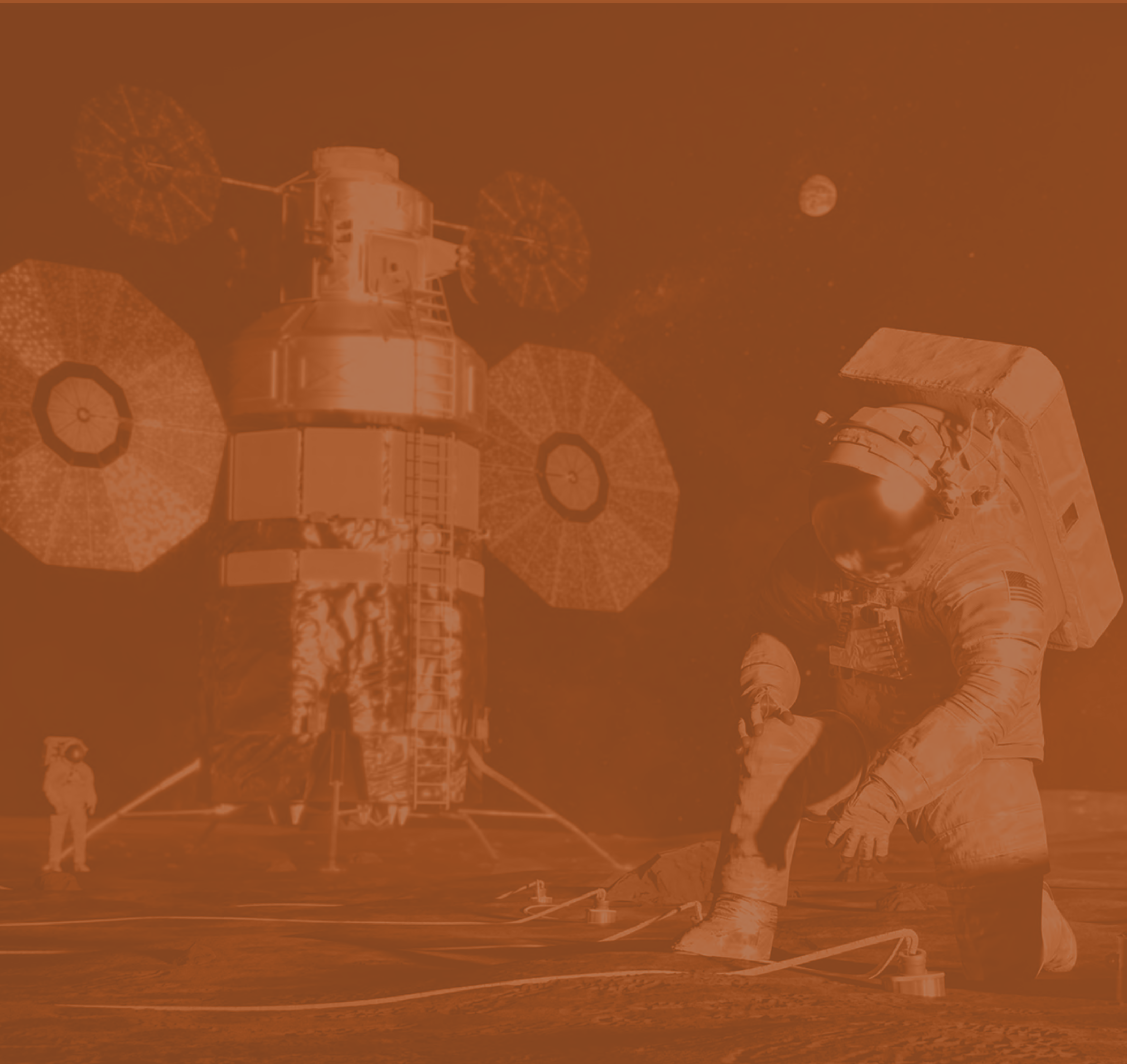
Currently, we have a lab setup of a NaI(TI)/CsI(Na) phoswich scintillator coupled with silicon photomultipliers, which occupies a much smaller volume compared to traditional photomultiplier tubes used in previous missions. We have developed a custom solution to perform pulse shape discrimination after analog integration of the signal. This lowered the energy threshold of the detector significantly while maintaining pulse separation power achieved by commercial hardware and software. Our lab measurements served as input to the FPGA design. The design is complete, and a prototype will be fabricated in FY21. The prototype will be tested in the lab for performance verification and further software optimization will be performed.

PRINCIPAL INVESTIGATOR: C. Michelle Hui

PARTNERS: University of Alabama in Huntsville

FUNDING ORGANIZATION: Technology Investment Plan

TECHNOLOGY AREA 10: Autonomous Systems



Tailored Oxidation Resistant High-Entropy Carbides for Hot End Engine Environments

OBJECTIVE: *To zero in on promising high entropy carbide compositions for oxidative corrosion environments and position NASA to adapt these materials into existing technology.*

PROJECT GOAL/DESCRIPTION

Ultra-high-temperature ceramics (UHTC) are a group of select transition metal carbide, nitrides, and borides with melting points in excess of 3,000 ˚C that also exhibit high hardness, elastic modulus, thermal shock resistance, and chemical attack resistance. They have become more and more relevant as increasing performance needs for rocket engines, jet engines, nuclear reactors, and hypersonic control surfaces dictate that the current state of the arts are no longer viable. High-entropy ceramics—and in this case, high-entropy carbides (HEC)—are a newly emerging family of UHTCs that have taken inspiration from high-entropy alloy development. The eight transition metal carbides (vanadium carbide (VC), titanium carbide (TiC), zirconium (ZrC), niobium carbide (NbC), molybdenum carbide (Mo_2C), hafnium carbide (HfC), tantalum carbide (TaC), and tungsten carbide (WC)) have been shown to form rock salt (Fm-3m) high-entropy solid solution. Single phase materials like this are stabilized by their enhanced molar configurational entropy ($\Delta S_{mix}=R\ln N$), where R is the universal gas constant, and N is the number of components), which reduces the Gibb's free energy of the system ($G=H-TS$), where H is the enthalpy, S is entropy, and T is temperature) by enhancing the $-TS$ term. As temperature increases, this entropy term dominates the free energy equation more, which suggests that these high-entropy materials should be exceptionally stable at elevated temperatures, especially against corrosion processes that have to compete against the free energy of the material.

APPROACH/INNOVATION

We will investigate four high-entropy carbide compositions. Based off the previous discussion about the composition of the passivating oxide, the specific compositions will be the following:

- $(Ti_{0.33}Zr_{0.33}Hf_{0.33})C$.
- $(Ti_{0.25}Zr_{0.25}Hf_{0.25}Ta_{0.25})C$.
- $(Ti_{0.25}Zr_{0.25}Hf_{0.25}Nb_{0.25})C$.
- $(Ti_{0.2}Zr_{0.2}Hf_{0.2}Nb_{0.2}Ta_{0.2})C$.

There is a high degree of confidence for successful synthesis of these compounds, primarily due to the fact that we have already fully synthesized sister compounds. They are:

- $(Zr_{0.5}Nb_{0.5})C$.
- $(Zr_{0.4}Nb_{0.4}W_{0.2})C$.
- $(Zr_{0.2}Nb_{0.2}Hf_{0.2}Ta_{0.2}W_{0.2})C$.

These compositions will be fully synthesized at MSFC using existing direct current sintering (DCS) technology.

The high-entropy carbides will be characterized to confirm the full solid solution has been formed. X-ray diffraction is an excellent tool for showing the formation of a single phase, as well as for determining lattice parameters, while scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) will give a secondary confirmation of full dispersion. In conjunction with SEM/EDS and x-ray powder diffraction (XRD), oxidation-based corrosion experiments will be performed here at MSFC with these compositions. The funding will allow us to set up an oxidation furnace for tests up to 1,800 ˚C, with a minimum of flowing air corrosion. Though, if processing and testing time allows, we will attempt to increase the capability to allow for dry oxygen (pure O_2) and wet oxygen (hydrothermal environments), which could then be incorporated into the test matrix. However, as it stands now, we will perform air-based oxygen corrosion on each high-entropy carbide composition from 700 ˚C to 1,800 ˚C. We will characterize mass change as a function of time, as well as perform XRD, SEM/EDS on the oxide scale that forms to fully assess oxidation behavior.

RESULTS/ACCOMPLISHMENTS

An extensive plan of testing and characterization is underway; however, delays due to COVID-19 site restrictions and lack of managerial support for 'nonessential' tasks have halted progress. Bulk specimen fabrication via DCS has been completed, with machining currently underway to produce TGA samples for oxidation corrosion testing. The test plan intends to run specimens every 100 ˚C between 700 ˚C and 1,800 ˚C for each specimen at a run time of 10 hr each. This would normally be followed up with XRD and SEM analysis of the oxidation scale formation to couple with the mass gain information to produce a full picture of the oxidation behavior. As of now, all this characterization work is pending on-site work approval.

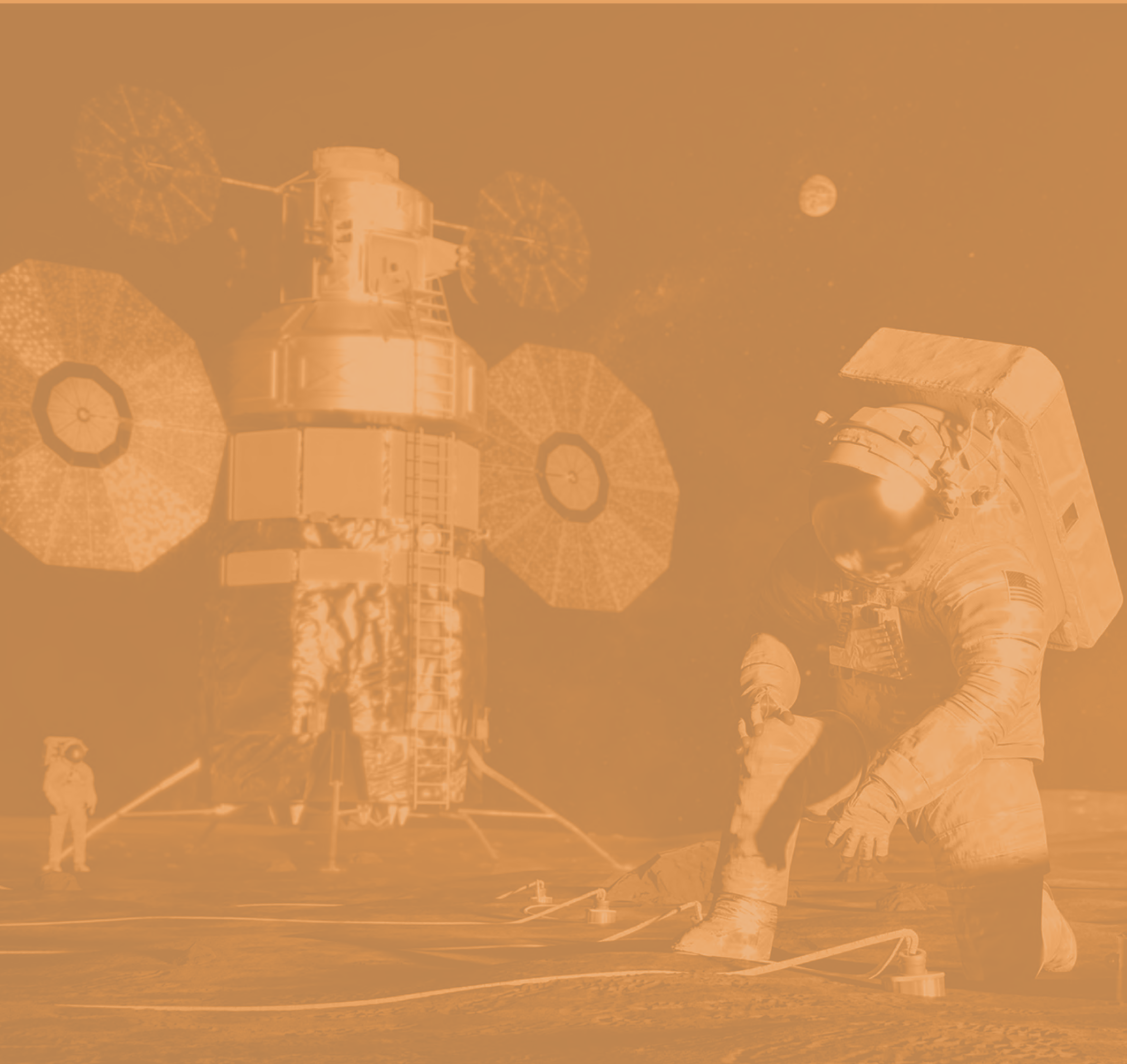
SUMMARY

High-entropy alloys and ceramics are a new field of mixed solid solutions that have been the topic of research as of late. For UHTCs, high-entropy carbides and borides present a new field of research that could be very promising, as the high entropy at which the system sits should help stabilize their corrosion resistance through entropic stabilization, while also allowing us to tailor the passivating corrosion layer that is formed through the selection of different constituents. While this is a low technology readiness level (TRL) at this point, this family of materials has the potential to either replace the state of the art or to be integrated into the current state of the arts. This could be as a coating material for C_f/C or as a new matrix material for ceramic fiber-reinforced UHTCs. As such, it is an incredibly valuable opportunity for NASA to enter in on ground level of this emerging technology so that we can zero in on useful high entropy compositions, improving technical capabilities and institutional knowledge. The ultimate aim by the end of this Center Innovation Fund would be to make recommendations on the feasibility of these materials for adoption into NASA technology and outline pathways to doing so.

PRINCIPAL INVESTIGATOR: Ryan Wilkerson
FUNDING ORGANIZATION: Center Innovation Fund

TECHNOLOGY AREA 11:

Software, Modeling, Simulation, and Information Processing



Development of a Dynamic Lightning Safety Algorithm for MSFC

OBJECTIVE: *To use the physical properties of clouds to determine when they can no longer support lightning to improve lightning safety protocols for MSFC activities, and ultimately, the public.*

PROJECT GOAL/DESCRIPTION

The goal of this project is to use multiple remote sensing datasets (satellite, lightning, radar) and machine learning techniques to develop an algorithm to identify when clouds can no longer support lightning. This analysis has led to the development of a prototype dynamic lightning safety algorithm during FY 2020 by the NASA Short-Term Prediction and Research Transition Center (SPoRT) team for future use by MSFC's Emergency Operations Center (EOC) and other personnel once the algorithm is vetted against current EOC lightning safety practices. This work is innovative because its overarching goal is to shift lightning safety standards from hard rules (30 min since last flash) to a dynamic algorithm that identifies exactly when the threat of lightning has ceased (mitigating over warning, and reducing down time). Conservative estimates indicate that MSFC could save upwards of $1 million due to lost time from the perceived threat of lightning if the proposed work could develop a reliable algorithm to end the stand down period of 10 min or more ahead of the standard 30-min rule used by National Oceanic and Atmospheric Association (NOAA) and MSFC.

APPROACH/INNOVATION

The innovation is in utilizing data synthesis techniques, which merge multiple observations to a single, physically-based evaluation to the real-time threat of lightning for MSFC. The novel way that the algorithm aligns the strengths of radar, lightning, and satellite datasets to provide integrated decision support services to MSFC (and eventually the commercial and public sector) is not matched anywhere else in our field. The other main unique feature is the machine learning generated model to indicate the location of flash initiation potential. This is the backbone of the algorithm and is solely in the possession of the team. The model output generates physically based assessments of lightning potential using all of the cloud property information available, then provides a 5–15 min likelihood that lightning will impact MSFC.

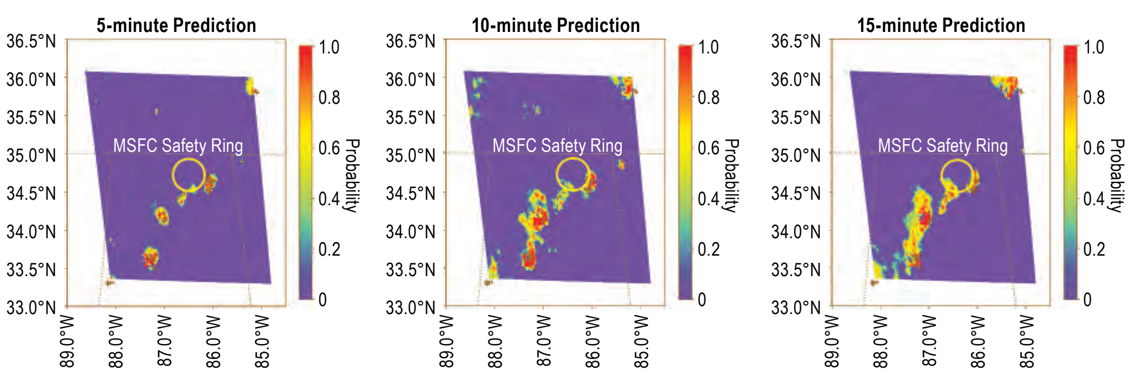


FIGURE 1. 5-, 10-, and 15-min lightning prediction probabilities near MSFC on April 7, 2019. The yellow ring indicates the 16 km safety buffer MSFC EOC uses to stand down due to lightning.

RESULTS/ACCOMPLISHMENTS

A total of 222 days where lightning was observed within 150 km of Huntsville in 2018 and 2019. Data from 2018 were used to develop a training dataset, and then 2019 was used to test machine learning model for skill score evaluation. Initial results for 5-, 10-, and 15-min predictions were strong, with the 5-min prediction performing best at ≈85% probability of detection (POD) and 20% false alarm rate (FAR) using a 2- by 2-km pixel verification method. The 10-min prediction remains similar in POD, but FAR increases to 40%. Much of this increase is due to the advection of storms with time, where the prediction lagged the storm motion.

SUMMARY

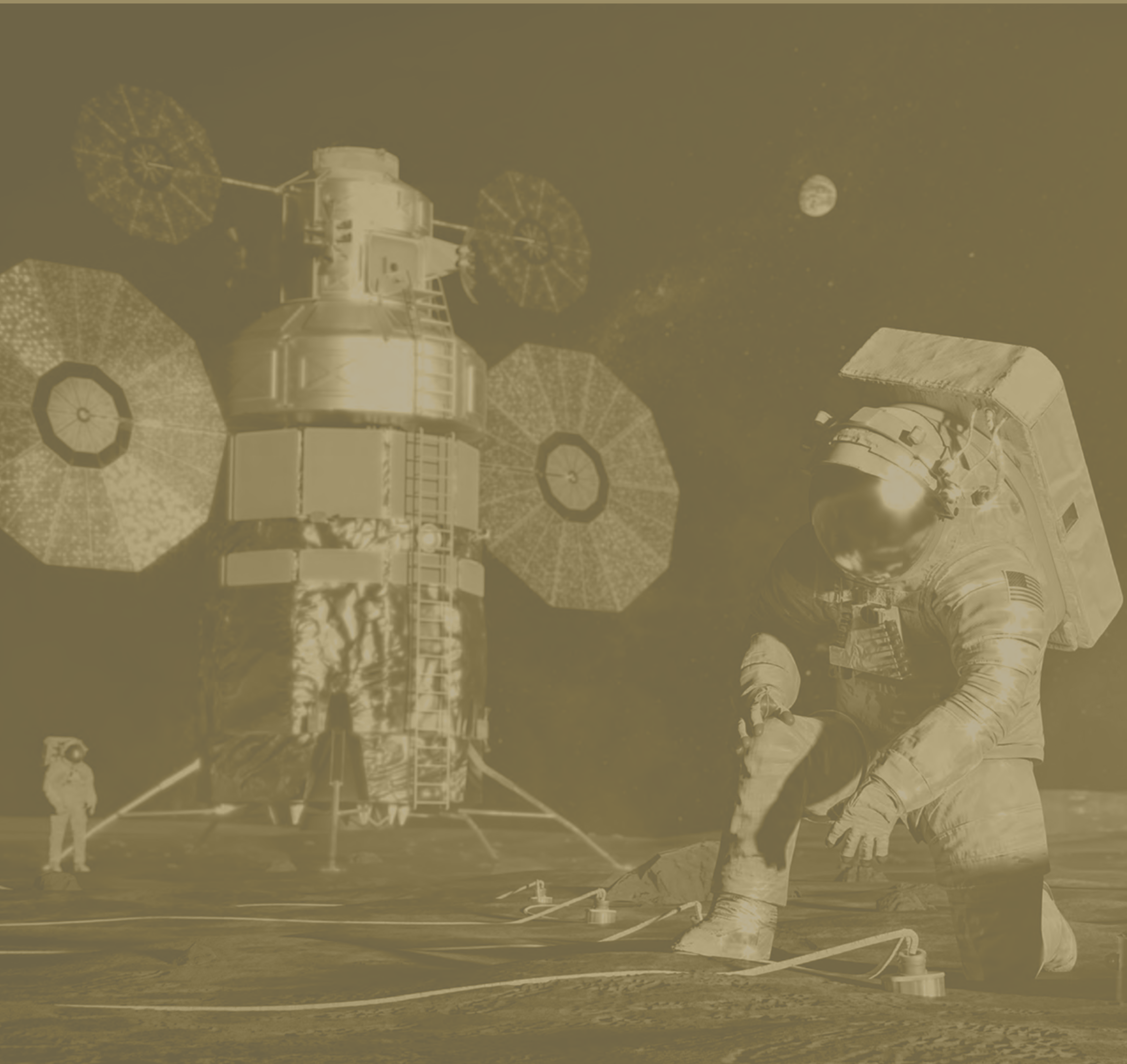
A prototype dynamic lightning safety algorithm was developed by the NASA SPoRT team to provide 5- to 15-min predictions on lightning occurrence to improve lightning safety and reduce downtime after a lightning threat is no longer possible. Initial results are strong with an 85% POD and 20% FAR for a 5-min prediction. Additional improvements are required to strengthen POD while decreasing FAR skill scores to increase accuracy, and application of this algorithm to understand impacts to lead time and reduction in additional downtime within MSFC's EOC protocols. This algorithm has grown from a technology readiness level (TRL) of 3 to a TRL of 5 during the FY 2020 year.

PRINCIPAL INVESTIGATOR: Christopher J. Schultz

FUNDING ORGANIZATIONS: Center Innovation Fund, Space Technology Mission Directorate, Science Mission Directorate

FOR MORE INFORMATION: www.weather.msfc.nasa.gov/sport/

TECHNOLOGY AREA 12:
Materials, Structures, Mechanical Systems, and Manufacturing



3D Printing and Laser Curing of Al/α-Fe_2O_3 Nanothermites for Gas and Strain Sensing

OBJECTIVE: *To develop on-demand carbon dioxide (CO_2) sensors for in-space manufacturing.*

PROJECT GOAL/DESCRIPTION

In-space manufacturing is developing novel materials and processes for on-demand printing of electronics and sensors in microgravity on the International Space Station as well as future habitats. This collaborative research with NASA and the University of Tennessee seeks to develop a new approach to printing and processing of sensors for in space applications. The use of extruded metallic pastes and low-power laser sintering will enable the capability to manufacture a wide variety of sensor and electronics for in-space applications, while requiring very low power overhead.

APPROACH/INNOVATION

In-space manufacturing is developing novel materials and processes for on-demand printing of electronics and sensors in microgravity on the International Space Station as well as future habitats.

Extrusion-based, on-demand printing of metallic pastes is a very feasible in-space manufacturing processing of sensitive printed sensors. This project objective was the development of aluminum nanoparticles combined with iron oxide (Fe_2O_3) nanowires that are optimized in a metallic paste developed in MSFC material laboratories for extrusion-based printing and laser sintering post processing.

FIGURE 1. Al-Fe_2O_3 electrode CO_2 sensor.

Various paste patterns were printed, including the interdigitated pattern shown in the previous illustration. Not only were a wide array of printed patterns possible, but the resolution of the printed patterns was better than anticipated.

The final development innovation was the use of in situ laser sintering of the printed layers of metallic paste. The power required for rapid in situ sintering of the aluminum metal was very low, making this process very attractive to in space manufacturing, where available power is often limited.

RESULTS/ACCOMPLISHMENTS

The research successfully demonstrated the capability to formulate metallic pastes for extrusion-based printing of a variety of sensors for monitoring environmental conditions. In the case of CO_2 sensing, the sensors fabricated by this method were quite responsive to changing CO_2 concentrations, making this a good choice for ISS habitat where CO_2 'bubbles' and high-concentration accumulation areas are known to occur. In addition, these sensors showed very good selectivity, meaning that they can differentiate CO_2 from other gases and substances in the environment.

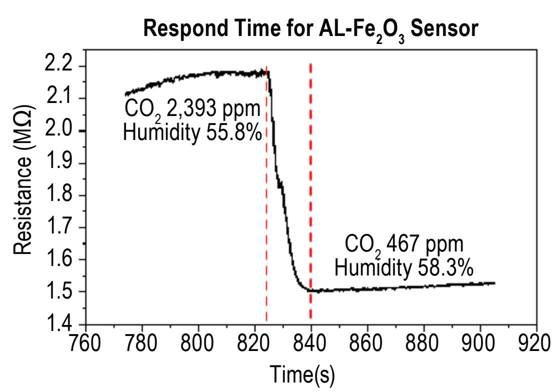


FIGURE 2. Respond time for Al-Fe_2O_3.

SUMMARY

The promising results from this research has led to further development of metallic pastes at MSFC as well as the addition of laser sintering capability to our 3D multimaterial printer. Further research of additional materials and optimization of the printing and laser sintering processes will lead to a wider array of in space manufacturing capability for a wider suite of on-demand printed sensors. These can be used by scientists to monitor their environment much more effectively in the future.

PRINCIPAL INVESTIGATOR: Anming Hu

PARTNERS: University of Tennessee

FUNDING ORGANIZATION: Space Technology Mission Directorate

3D-Printed Electronics Packaging

OBJECTIVE: *To improve 3D-printed electronics packaging with electroplating.*

PROJECT GOAL/DESCRIPTION

Electronics packaging for space applications has a unique set of engineering challenges. Some of these challenges include electromagnetic interference (EMI) containment, thermal conductivity, extreme temperatures, UV light exposure and the ever present need to design parts that are small and lightweight. Due to the low mass of most electronics, the packaging is often overbuilt simply because very thin wall features are difficult to machine.

Three-dimensional-printed avionics packaging can help create small and lightweight packaging; however the plastics used in 3D printing have their own drawbacks. The plastics are often flammable, they are UV light sensitive, they have off-gassing problems, they do not conduct heat well, and most do not block EMI and are not electrically conductive.

Nickel plating the 3D-printed plastic offers an opportunity to mitigate the road blocks that prevent it from being used as space flight hardware. This CIF is to investigate how well nickel plating blocks out the UV light, shields from EMI, makes the packaging more electrically and thermally conductive, how it prevents off-gassing, and other physical properties of nickel plated plastic.

APPROACH/INNOVATION

If nickel-plated, 3D-printed avionics packaging is to be accepted as flight hardware, understanding of the physical properties must be increased. To increase understanding an electroplated, 3D-printed electronics enclosure will be compared to a nearly identical enclosure created by more traditional means.

The different fabrication methods will be compared on key metrics and by tests that are frequently performed on electronics packaging. The key metrics that will be compared are cost, weight, fabrication time, and part count. The tests used to compare are electromagnetic emission tests, thermal conductance, vibration, electrical grounding, and off-gassing.

A key partnership in this project is with Repliform Inc. Repliform is a company that has 20 years of experience electroplating plastic parts to improve their mechanical performance. They have offered technical support and customization options for the plating process. The 3D-printed parts were sent to Repliform for plating using their proprietary process that has been developed over years of experience.

Assuming that the results of the tests prove this technology as a viable design option, future work will be done to implement this technology on flight projects.

RESULTS/ACCOMPLISHMENTS

Progress has been made on the fabrication and assembly of the enclosures. Two enclosures were printed at MSFC with a stereolithography process on Formlabs 3D printers. Those two enclosures were printed using the Formlabs high temperature resin. Two additional enclosures were printed by 3D Hubs using a multi jet fusion process on powdered nylon. The parts were sent to Repliform for electroplating.

The 3D-printed parts were plated first with .004 in of copper then .006 in of nickel. The copper is a necessary first step to get good adhesion of the nickel. The copper also has good thermal conductive properties.

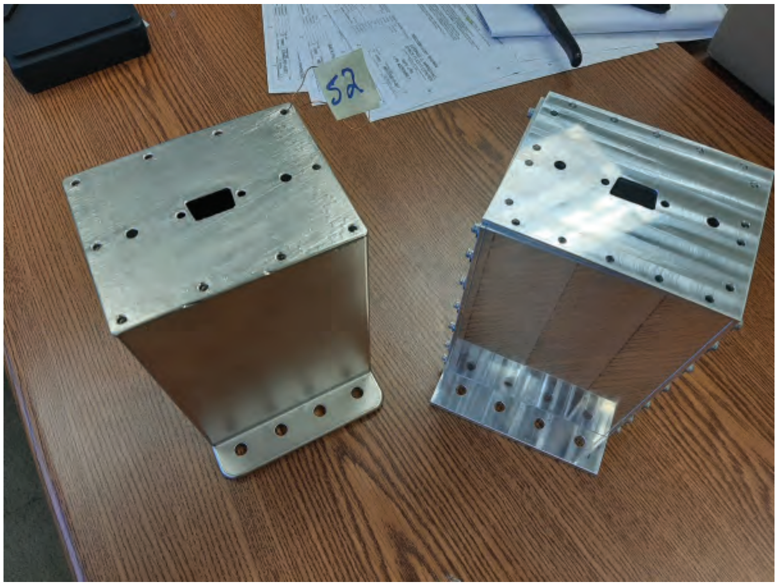


FIGURE 1. Electroplated 3D-printed box next to traditionally machined box.

An almost identical enclosure was made from milled 6061 aluminum parts using traditional design and fabrication processes, basically a six-piece box with slots to hold electronic boards and many small screws along the edge to hold the box together.

The global pandemic and a stay of nonessential work at MSFC has prevented any testing of the avionics enclosures so far this year. As MSFC reopens, testing will start for the avionics boxes.

SUMMARY

Three-dimensional printing has existed as a manufacturing method for some time, yet for many reasons, has not seen widespread use in electronics packaging for spaceflight. By electroplating 3D-printed parts with metal, many of the limitations of plastic parts in spaceflight can be overcome. Additionally, the inherent benefits of 3D printing can finally be utilized. Testing will prove whether or not this technology will help move 3D printing from a novelty to a common and proven manufacturing method.

PRINCIPAL INVESTIGATOR: Jarret Bone

PARTNERS: Repliform Inc.

FUNDING ORGANIZATIONS: Center Innovation Fund, Space Technology Mission Directorate

Enhanced Equipment Isolation in Extreme Vibratory Environments Using Rotational Inertial Devices

OBJECTIVE: *To develop a vibration mitigation device (VMD) that combines passive isolation and damping (rotational inertial device) into a single VMD.*

PROJECT GOAL/DESCRIPTION

NASA hardware is subject to extreme vibratory environments. These environments can make it difficult to mitigate damage to avionics boxes and other equipment. This problem is of particular importance when using legacy hardware in new systems with higher predicted environments, such as the Space Launch System and Orion spacecraft. A traditional solution to these vibration concerns is low-stiffness isolation mounts. The isolated system's low stiffness, thus the low isolation frequency effectively controls the acceleration response of the equipment it is attached to when considering a broadband loading; however, this decreased stiffness and low isolator natural frequency would cause the equipment to be subjected to excessive displacement and acceleration response at low-frequencies due to transient excitation.

The objective of this collaborative project between the University of Tennessee and MSFC is to provide a proof of concept for, and assess the feasibility of, an equipment vibration isolation system for NASA hardware that features rotational inertial devices. An architype isolation system considering the needs of MSFC will be established. As this project is an intermediate step towards further development, only loading and response in one direction will be considered in this architype system. Analytical and numerical modeling and optimization will be performed to determine the most beneficial set of parameters and configurations of a rotational inertial device. Simulated flight hardware with an isolation system featuring rotational inertial devices will be designed, fabricated, and experimentally tested. Based on these test results, a series of more advanced simulations will be undertaken.

APPROACH/INNOVATION

This work seeks to leverage recently developed rotational inertial devices and combine them with isolation systems. While these rotational inertial devices have taken various forms, their common feature is a mechanical device called an inerter. The inerter is a two-terminal mechanical device that produces a rotational inertial mass proportional to the relative acceleration between its two terminals; see figure 1 for common realizations of this device. Through the transformation of linear motion to rotational

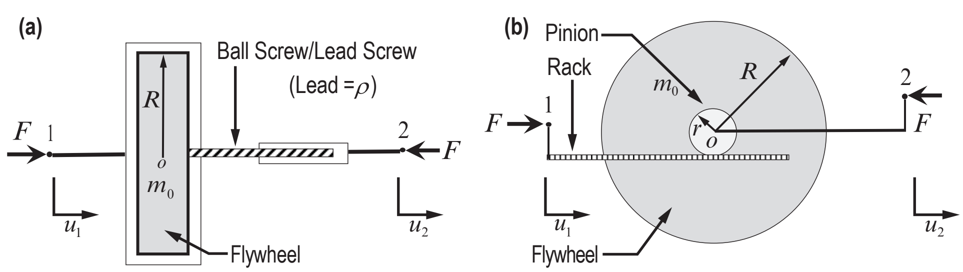


FIGURE 1. Common realizations used for inerters (a) ball screw /lead screw and (b) rack and pinion.

motion, the inerter can provide a large mass amplification, thus producing an effective large inertial mass through a physically small flywheel mass.

An example of an inerter-based isolation system is shown in figure 2. In general, studies on inerter- based isolation systems have found that they are capable of significantly reducing the displacement response of the isolated system without increasing their acceleration response. While previous studies of inerter-based isolation systems have shown promise in leveraging these mass effects for the vibration control of civil systems, these studies have largely not considered the unique demands of aerospace applications.

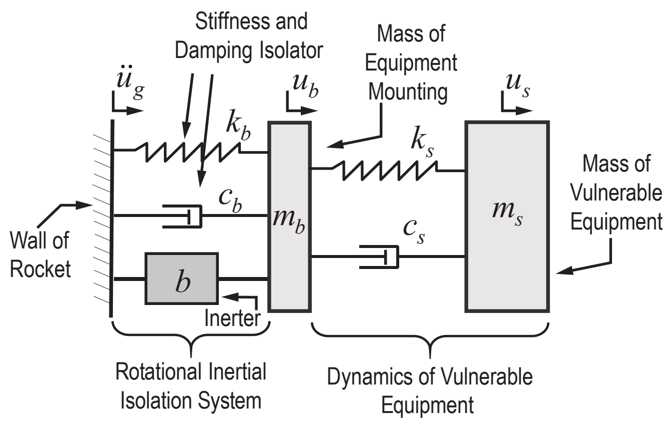


FIGURE 2. Dynamic model of equipment with rotational inertial isolation.

RESULTS/ACCOMPLISHMENTS

While this project has only recently started, the architype model for the isolated system considered has been established, and the numerical and analytical modeling of this isolated system is underway. This project is proceeding as scheduled, and it is on track to experimentally demonstrate the effectiveness of the studied rotational inertial isolation system. The results of this study are expected to encourage future development and investment to bring these systems to commercialization.

PRINCIPAL INVESTIGATOR: Nicholas Wierschem

PARTNERS: University of Tennessee

FUNDING ORGANIZATION: Cooperative Agreement Notice

Metal 3D Printing Using High-Pulsed Power

OBJECTIVE: *To create a cost-effective, versatile 3D printer for metal applications.*

PROJECT GOAL/DESCRIPTION

Three-dimensional printing of metals is desired to create new structures not available to forging or molding. The original project planned to fire high-voltage, high-current, short-pulse-width electrical discharges through a powder bed and test for fusion. The expectation is that the Lorentz force from the electrical discharge would both provide the heat to melt and fuse and the compressive force to eliminate voids and create a stronger part. The conceived pulser facility is illustrated below. Each brick is a 300-lb capacitor capable of discharging at 40 kA. Eight of these capacitors would discharge through a common plate, shown in expanded view. The small cylinder on top is the test section where powder would be fused.

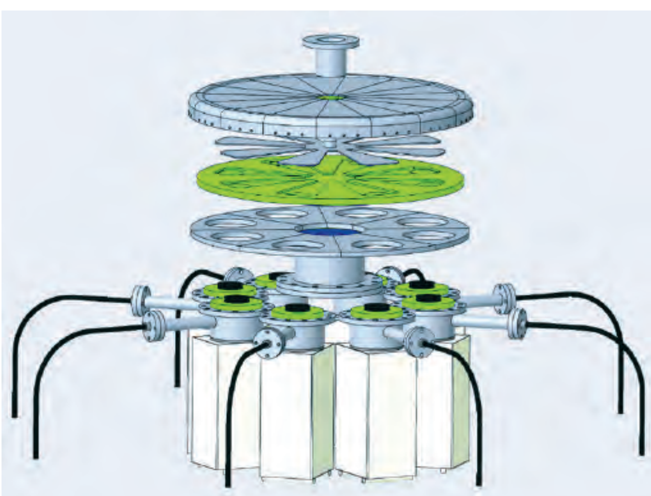


FIGURE 1. The Charger 2 Pulsed Power Facility.

Due to the inability to work at MSFC facilities during the COVID-19 pandemic the team vectored to development of a micro-rail gun that uses lower voltage, current to melt and accelerate a small droplet of metal. This droplet would be aimed at already printed material with the intent to fuse and build up the part.

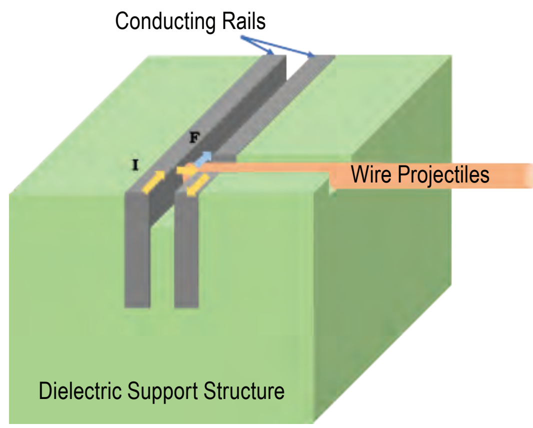


FIGURE 2. Schematic of the micro-rail gun system.

APPROACH/INNOVATION

Figure 2 illustrates the components used to examine proof of concept. The gap between the conductive rails is 150 µ. The 150-µ wire is the feed stock that forms into metal droplets through $I^2 R$ heating when it completes the circuit between the rails that are connected to a 20-V battery. The current flowing through the wire also creates a force on the wire drop equal to:

$$F = \frac{\mu_o I^2}{2\pi} \ln\left(\frac{d-r}{r}\right)$$

where I is the current flowing through the metal droplet and rails, d is the diameter of the droplet, r is the spacing between the rails, mo is the permeability of free space 1.256×10^{6} H/m, and $p = 3.14159$.

Currents of 30A can provide sufficient acceleration to reach velocities in excess of 200 mps when exiting a 3-cm rail. Such velocities would enable to droplet to reach a print form while still fluid but may need to be reduced to prevent spallation. The optimum currents would need

FIGURE 3. Current representation of the micro-rail gun system.

to be determined through experimentation with the desired plating materials.

RESULTS/ACCOMPLISHMENTS

Before quarantine, the team had finished assembling a single capacitor for the Charger 2 facility. That system was undergoing tests. Also, the team had constructed a plate for a three capacitor version. Currently, the team has conducted several firings with various stock material, including silver, platinum, and palladium. The rail system is comprised of stock aluminum. To date, we have succeeded in creating droplets and moving them down the rail, but they have not escaped the rail and struck a downrange target. The team continues to experiment with different current levels, different stock materials and is currently trying different rail materials.

SUMMARY

Due to COVID-19, the team had to vector away from the expected project and started looking at new methods to use high-power pulse technology to create a new type of metal 3D printer. Both concepts, the high-power systems designed to fire through powder beds and the micro-rail gun system, are still in the early stages of experimentation. No unexpected challenges have occurred, and the team is hopeful for success in the future.

PRINCIPAL INVESTIGATOR: Robert Adams

PARTNERS: University of Alabama in Huntsville, Bill Seidler, William Kaukler

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group, Technology Investment Plan

FOR MORE INFORMATION: www.nasa.gov/puff

Composite Technology for Exploration (CTE)

OBJECTIVE: *To composite technologies with a focus on weight-saving, performance-enhancing bonded joint innovations for heavy-lift launch vehicle-scale applications to support future NASA exploration missions.*

PROJECT GOAL/DESCRIPTION

The Composite Technology for Exploration (CTE) project is developing and demonstrating critical composite technologies for future NASA exploration missions with a focus on composite joint technologies for Space Launch System (SLS)-scale composite hardware. CTE is improving the analytical capabilities required to predict failure modes in composite structures. The project supports SLS payload adapters and fittings by maturing composite bonded joint technology (longitudinal and circumferential) and analytical tools to enable risk reduction. Composite joints can account for significant increases in cost and weight. Through materials characterization studies; advanced analysis tools; and the design, manufacturing, and testing of lightweight composite bonded joint concepts, CTE is producing weight-saving, performance-enhancing composite bonded joint technologies. CTE is developing and validating high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints. By applying this comprehensive approach, composite technology will progress and improve bonded-joint failure load and mode predictions to increase overall confidence of bonded joint composite structures.

APPROACH/INNOVATION

When properly designed, composite structures have many potential benefits over traditional metallic structures, including lower mass, better fatigue resistance, lower part count, and reduced life-cycle cost. NASA is advancing composite technologies that provide lightweight structures for future exploration missions. Due to the large diameter of a heavy-lift type launch vehicle and the unavailability of large autoclaves for curing composite structures, individual large composite panels must be manufactured separately and then joined together. The state-of-the-art method for joining launch vehicle composite panels and structures uses metallic joints that are both heavy and labor intensive. The CTE Project is allowing NASA to gain experience with lightweight composite joints and analysis techniques specifically applicable to large-scale composite structures. CTE has designed, fabricated, and tested a lightweight bonded joint concept for the SLS Payload Adapter. The project is also developing and validating high-fidelity analysis tools/modeling and analysis standards for the prediction of failure and residual strength of composite bonded joints.

ACCOMPLISHMENTS/RESULTS

LONGITUDINAL BONDED JOINTS

After demonstrating an out-of-oven manufacturing process for longitudinal bonded joints on the SLS manufacturing demonstration article (MDA), longitudinal bonded joints were baselined by the SLS payload adapter to reduce weight and manufacturing time. The project has continued to improve the high-fidelity analysis tools/modeling and analysis standards for the prediction of failure and residual strength of the longitudinal composite bonded joints.

CIRCUMFERENTIAL BONDED JOINTS

Over the last year, the CTE project has focused on developing and demonstrating 3D-woven composites for circumferential bonded joints. A circumferential bonded joint includes a C-channel and pi-pre-

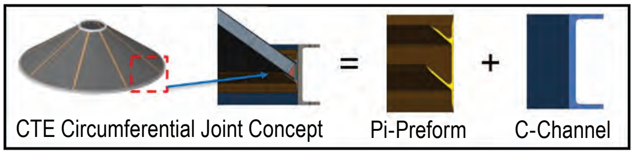


FIGURE 1. Circumferential joint concept.

form bonded together (figure 1). Both the C-channel and pi-preform are made from 3D-woven fibers. The resin-transfer molding (RTM) process is used to infuse and cure the 'dry' 3D-woven C-channel. Additional 36-in C-channel parts were made using updated manufacturing processes. From the latest manufactured C-channels, additional coupon testing is being performed as well as a large-scale circumferential joint test article. This large-scale test article will be tested to evaluate scale up as well as provide additional data for verification of analysis models (figure 2). This will further the understanding of damage in 3D-woven composites, specifically the complex geometry related to C-channels and support failure initiation and propagation. Continued development of the manufacturing process and testing will increase overall confidence of bonded joint composite structures.

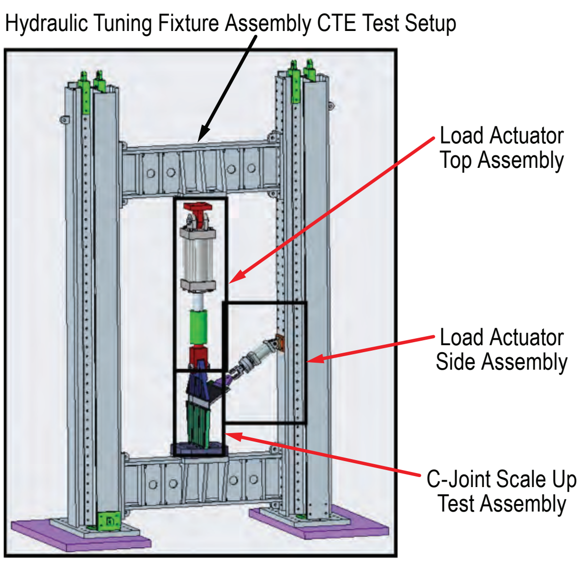


FIGURE 2. Test setup of large-scale circumferential joint test article.

SUMMARY/CONCLUSION

The potential benefits of CTE's composite joints technology development activities include weight savings, cost savings, and improved performance with increased reliability compared to metallic structures/joints. The project is enabling the technology infusion of lightweight composite joints into future exploration missions. CTE is working to achieve these potential benefits by developing and validating high-fidelity analytical tools and standards for predicting failure and the residual strength of composite bonded joints. This provides an understanding of composite discontinuities, a path toward certification, and a reduction of risks while increasing confidence in composite joint technologies.

PRINCIPAL INVESTIGATORS: John Fikes, Mallory Johnston

PARTNERS: NASA Langley Research Center, Goddard Space Flight Center, Glenn Research Center

FUNDING ORGANIZATION: Space Technology Mission Directorate

FOR MORE INFORMATION: https://gameon.nasa.gov/projects/composite-technology-for-exploration-cte/

Long Life Additive Manufacturing Assembly (LLAMA)

OBJECTIVE: *To significantly reduce risk to a lander system while demonstrating the reliability of the additive manufactured thrust chamber assembly hardware to provide a path for qualification for this manufacturing technology to be fully used in a lander or in-space system.*

PROJECT GOAL/DESCRIPTION

The Long Life Additive Manufacturing Assembly (LLAMA) task will conduct a hot-fire test demonstration of a high-duty cycle lander concept rocket thrust chamber with throttling capabilities fabricated through additive manufacturing (AM). LLAMA will also determine the performance of the GRCop42 alloy selected for the thrust chamber and identify a path forward to qualifying GRCop42 for flight applications. The LLAMA task will demonstrate high-risk, off-nominal testing to understand the reliability of the additive manufactured thrust chamber assembly (TCA) hardware before subsystem or full system development and provide data to lander and commercial lander projects. Data to be collected includes cycle tests of up to three immediate restarts of 10- to 20-s mainstage durations with 10-s delays between tests and the material properties of the additive manufactured components. The project will complete testing to meet a 50× start requirement while providing integration with subsystems and understanding of the stability data for the throttled subsystem.

FIGURE 1. 7,000-lbf Chamber and Nozzle.

The project goals are:

(1) Complete rapid fabrication and testing of a lander concept thrust chamber with the key goal of demonstrating high-duty cycle and high-performance targeting throttling capabilities.

(2) Perform hot-fire testing meeting a minimum of 50 starts that targets mid-throttling level capabilities for lander technology.

(3) Complete destructive evaluation of chamber following testing to determine material performance and reporting for characterization of materials.

APPROACH/INNOVATION

The LLAMA team, consisting of MSFC and GRC personnel, will coordinate with outside vendors for fabrication of injector, thrust chamber, and nozzle components. Test plans have been developed for testing at Test Stand 115 (TS115) at MSFC. Testing will be performed in two phases: with an additively manufactured directed energy deposition (DED) NASA HR-1 regenerative nozzle and composite nozzles installed. Following the completion of testing, the thrust chamber will be destructively sectioned to enable inspection to quantify the performance of the GRCop-42 alloy in this application. The results from the testing campaign and the destructive evaluations will be detailed in the final report.

LLAMA will demonstrate the rapid development of a TCA by quickly fabricating hardware using AM technologies and starting setup within six months of project Authority to Proceed (ATP). The project will complete hot-fire testing encompassing a minimum of 25 cycles on a copper alloy GRCop-42 additive manufactured chamber and 25 cycles with an added high temperature carbon-carbon nozzle. Hot-fire testing will demonstrate active and passive throttling capabilities and stability. These tests will also demonstrate immediate restarts for hardware durability, the stability of the injector, and a path towards qualification on the GRCop-42 material to enable use during flight in an as-built additive surface condition. After testing is completed, a destructive evaluation of the chamber will be conducted to determine material performance and characterization of the GRCop-42 material.

FIGURE 2. Setup at MSFC TS115.

RESULTS/ACCOMPLISHMENTS

The project was able to complete the manufacture of the GRCop-42 chambers in a timely manner that would have allowed for the start-up of testing within the 6 month timeframe. The project objective to quickly fabricate hardware using AM technologies and start setup for testing within six months of project Authority to Proceed (ATP) was impacted by COVID-19. The test area was shut down because of COVID-19, thus not allowing the project to meet this metric. The 7,000-lbf-thrust chambers were manufactured from GRCop-42 powder using the laser powder bed fusion (L-PBF) AM techniques. The chambers were visually inspected and sent to other vendors for cleaning, machining, and polishing of the chamber exterior and hot wall. One of the chambers was then mounted to a nozzle manufactured using a DED additive process from NASA HR-1 powder material in order to leverage LLAMA to test the DED nozzle technology. The TCA is currently installed at TS115 in preparation for the first series of testing. The high-temperature composite nozzles have also completed fabrication. Each of these nozzles were designed and manufactured at three separate vendors. The high-temperature composite nozzles will be attached to the L-PBF GRCop-42 chambers and tested for multiple cycles. The project will conduct material performance and characterization by destructive evaluation of the chamber following hot-fire testing.

SUMMARY

Continued technology maturation of in-space propulsion systems is key to the success of NASA's exploration goals for Lunar and Mars missions. Elements of NASA's vision and Strategic Plan include reducing life cycle development time and costs, along with reducing system weight and improving performance through the use of state-of-the-art AM techniques to fabricate liquid rocket engine components. LLAMA will support this technology initiative by conducting a high-duty cycle (reusable) test demonstration of a lander concept rocket thrust chamber fabricated through AM. The manufacturing processes will be evaluated in a relevant environment and material characteristics will be developed and documented.

PRINCIPAL INVESTIGATORS: Paul Gradl, Chris Protz, Tom Teasley

FUNDING ORGANIZATIONS: Space Technology Mission Directorate, Game Changing Development

Vitro-Lube Environmental Exposure Test

OBJECTIVE: *To create a database of the wear/degradation properties of Vitro-Lube before and after exposure to some common test stand/launchpad environmental conditions (ultraviolet (UV) and 'salt fog'). Vitro-Lube is a ceramic-bonded dry film lubricant that is used on many flight hardware components (ex: BSTRA joint, sliding bellows, solid rocket boosters, etc).*

PROJECT GOAL/DESCRIPTION

Having a database that exhibits the behavior of the tribological properties of the Vitro-Lube that summarizes how this dry lubricant degrades after exposure to the test stand environment is of great interest to the aerospace community and NASA. It is well known that this coating does not inhibit corrosion, and the manufacturer highly recommends using corrosion-resistant substrates to mitigate this problem. It is also known that contamination of the wear surfaces will trigger detrimental wear behavior of the coating.

Flight hardware often sits on a test stand or launch pad for extended periods of time while exposed to a corrosive environment. There is currently no performance data on Vitro-Lube that accounts for these environmental conditions (humidity, sunlight, salt, etc.) during sustained exposure. We will address this by performing tribological testing on specimens made from nickel alloy 718 (UNS N07718) with Vitro-Lube applied.

APPROACH/INNOVATION

Vitro-Lube is a ceramic-bonded dry film lubricant that uses MoS_2 and graphite as lubricating pigments and is marketed by National Process Industries, Inc. (NPI). Vitro-Lube is applied to many spaceflight components, including most-particularly nickel-alloy components. No engineering data exists regarding any possible Vitro-Lube degradation after extended exposure to coastal environments encountered by flight hardware on test stands or launch pads. Such environments will include ultraviolet (UV) ray, high humidity, and salt exposures. In this study, nickel-alloy disks coated with Vitro-Lube by NPI, will be exposed to controlled UV ray and salt fog environments in facilities available at MSFC and then run in tribological pin-on-disk tests to quantify any difference in coating lubricity or wear compared to coated disks that were not exposed to those environments. Successful completion will provide definitive data regarding the behavior of Vitro-Lube coating. This data should benefit NASA and other industry users of Vitro-Lube as to the environmental hardiness of the coated hardware, flight or otherwise. Results of the completed study will be distributed to different MSFC organizations and also other NASA Centers such as Glenn Research Center (GRC), JPL Jet Propulsion Laboratory (JPL) and Langley Research Center (LaRC), in addition to the U.S. Air Force.

RESULTS/ACCOMPLISHMENTS

For test specimen fabrication, all 21 specimens have been machined. All of the specimens were then shipped to NPI for coating and then returned to MSFC. Every specimen was measured after coating application using noncontact profilometry to characterize the surface condition and changes. Two representative samples were measured before coating application.

SUMMARY

Due to the pandemic, testing on the Vitro-Lube samples has being delayed. However, testing is approved to begin in October 2020.

PRINCIPAL INVESTIGATOR: Sara Rengifo
FUNDING ORGANIZATION: Technical Excellence

Lightweight Composite Payload Fairing Development

OBJECTIVE: *To develop lightweight composite fairing requiring no thermal protection system (TPS).*

PROJECT GOAL/DESCRIPTION

Current state-of-the-art sandwich composite payload fairings use secondarily bonded TPS that adds significant weight to the structure. The proposed concept, through testing, proved that no TPS will be required on the structure leading to weight saving.

APPROACH/INNOVATION

The key technical challenge of the proposed research was selecting the composite material and its processing to achieve the goal of survivability under ascend-phase heat loads of launch without any TPS. The goal was achieved using carbon/phenolic composite with modified cure cycle. Successful hot-gas testing performed last year without any failure proved the design concept. This year's deliverables are mechanical and acoustic testing. All the test results (hot gas, mechanical and acoustic) will assist payload-fairing designers to design lightweight fairing. A literature search showed no industry or academia has developed processing of phenolic composite like the proposed effort. The next step is to share the test data with the SLS payload fairing designers for evaluation.

FIGURE 1. Before and after hot-gas test panel photograph, indicating no damage to outer skin.

RESULTS/ACCOMPLISHMENTS

Three sandwich composite (carbon/phenolic skins with aluminum honeycomb core with modified cure cycle) panels were subject to hot-gas testing. MSFC thermal group provided the heat loads. The panels were tested at highest heat load, which a SLS (cargo) fairing will be subjected to during ascend phase of the launch. Each panel was cured separately to study the processing effect on the performance. Table 1 shows the tunnel conditions and surface/back side temperature of the composite panel. No delamination and ply lift of the composite panel was observed during the test, which was also proved by the NDI results.

FIGURE 2. Atlas-V payload fairing with P50 cork.

SUMMARY

The hot-gas test results showed that the sandwich composite payload fairing can fly without any TPS, leading to weight saving. The saving may vary from 20% to 30% depending upon the size and flight loads. Weight saving results into increase in the payload capacity, which will be important for future deep space missions launches.

TABLE 1. Tunnel conditions and surface/backside temperature of the composite panel.

Run Number	Test Panel ID	TPS Description	Average	Reference Call	Calc Combustor Temp	P912	P922	P932	Wall Angle	AFR	Qdot Cold Wall	Actual Run Time	Actual Test Load	Backside Sunstrate Temperatures				Max IR Surface Temperature
			mils		°F	psig	psig	psia	deg		BFS	sec	BTU/ft²	T/C I.D.	Start Temp (°F)	EOT Temp (°F)	Max Temp ~1 Min Soak (°F)	IR2501 (°F)
18-0198	PLF-06-08-2018	Composite AL Honeycomb		18-0195, 18-0196 Avg	1,944.47	786.012	581.525	160.512	1.006	92.879	5.002	59.93	299.76	T2201	82.23	152.63	196.10	516.36
														T2202	82.09	176.42	241.74	
18-0199	PLF-06-15-2018	Composite AL Honeycomb		18-0195, 18-0196 Avg	1,947.74	785.700	579.849	160.215	1.006	92.655	5.002	59.95	299.89	T2201	87.87	158.33	195.63	532.54
														T2202	87.83	168.07	226.13	
18-0200	PLF-06-20-2018	Composite AL Honeycomb		18-0195, 18-0196 Avg	1,949.78	785.418	578.704	159.833	1.005	92.509	5.002	60.03	300.26	T2201	90.04	154.26	196.02	530.04
														T2202	89.92	181.37	243.23	
18-0201	PLF-06-08-2018 Second Run	Composite AL Honeycomb		18-0197	2,087.97	908.615	610.587	174.531	8.520	84.312	10.106	201.90	2,040.41	T2201	92.34	395.21	410.19	812.17
														T2202	93.39	415.40	437.09	

PRINCIPAL INVESTIGATOR: Raj K. Kaul

FUNDING ORGANIZATIONS: Technical Excellence, Cooperative Agreement Notice

Damage Tolerance Characterization and Environmental Sensitivity of Custom 465 Alloy to Support NASA Technology

OBJECTIVE: *To collect damage tolerance and notch sensitivity data at ambient and cold temperatures on ultra-high strength, precipitation-hardened stainless steel.*

PROJECT GOAL/DESCRIPTION

Custom 465 is an ultra-high strength, precipitation-hardened stainless steel alloy. The strength capability of the material makes it attractive for highly stressed components with small or compact geometries. NASA applications include pins, clevises, fittings, and other hardware used in ground support equipment and structural test equipment for Space Launch System hardware. Limited data are available that characterize the strength, ductility, and damage tolerance behavior of the material at ambient and cold temperatures. In this study, smooth and notched tensile tests and crack growth rate tests were conducted at ambient and cold temperatures to evaluate the strength, notch sensitivity, and damage tolerance behavior of the material.

APPROACH/INNOVATION

Typical applications of Custom 465 stainless steel include parts requiring good stress corrosion resistance, high strength, and high fracture toughness. Primarily, the service environments are at ambient or elevated temperature conditions. Typically, high-strength steels are not rated for use at low temperatures due to loss of ductility and increased sensitivity to notches and cracks, i.e., areas in the hardware where the local stress is amplified. As a result, data at cold temperatures for these alloys is not commonly collected. In this study, data was collected at ambient (70 °F) and cold (–65 °F) temperatures to evaluate the effects of temperature on behavior of the material at notches and the crack growth rate behavior of the material in an effort to increase understanding of the material at lower temperatures. Notch tensile testing, as the name implies, is a measure of the material strength in the presence of a geometric discontinuity or notch in the material. Notched materials with ductile capability exhibit higher tensile strengths than the corresponding smooth sample. Crack growth rate testing, as the name implies, is a measure of the crack extension that occurs when a material is cyclically loaded. Crack growth rates of a material are necessary to evaluate service life capability of parts with cracks that are subject to cyclic or fatigue loading during their operational life. The data generated in this study lends insight into material static and cyclic capability at cold temperatures. Material properties at these temperatures are not commonly reported in material property datasets. Understanding material behavior at these temperatures expands the design space for the material and promotes design solutions where an ultra-high strength material is needed.

RESULTS/ACCOMPLISHMENTS

The Custom 465 alloy used in this study was precipitation heat treated to the H1000 condition. This is a common heat treat condition for the material. Smooth and notched strengths for the material are shown in the table. Note the material strength increases at the lower tempera-

TABLE 1. Smooth and Notched Tensile Strength Behavior.

Temperature (°F)	Smooth Sample Tensile Strength (ksi)	Notched Sample Tensile Strength (ksi)	Notch Strength Ratio
70	232	368	1.6
–65	250	333	1.3

ture. This is not unexpected for precipitation hardened stainless steels. Note also, the notch strength ratio is greater than one at the ambient temperature, indicating the material is not notch sensitive. Of particular interest is the notch ratio at the cold temperature, which is also greater than one, indicating the material is not notch sensitive at the cold temperature. The notch-strength ratio is decreasing as the temperature decreases, but the cold test temperature still retains good notch ductility. This attribute of the material is important in high-strength material selection for complex shapes with geometric discontinuities.

Crack growth rate data are shown in the figure. These data describe the rate of crack growth per load cycle (da/dN) as a function of the cyclic stress intensity range at a crack tip (ΔK). Of particular note in this data is for a given cyclic stress intensity range (choose a ΔK value on the horizontal axis), the corresponding crack growth value (da/dN) is lower for the material at cold temperatures (blue data points) than it is at ambient temperatures (violet data points). This indicates the crack growth rate is slower at cold temperatures. Data collected in these tests can be used to develop crack growth rate material models that can be used in service life analysis software.

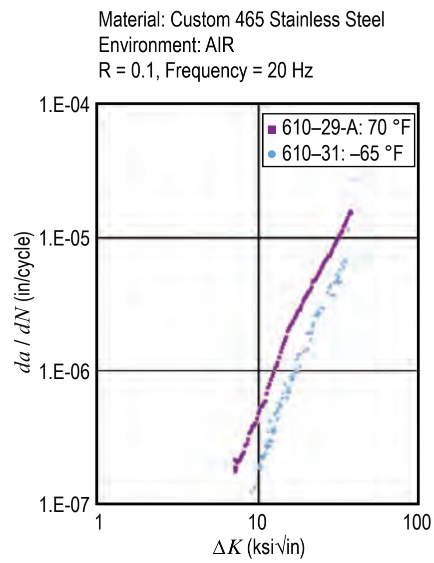


FIGURE 1. Crack growth rate data.

SUMMARY

The study generated test data describing cold temperature environmental sensitivity of Custom 465 stainless steel, an ultra-high strength, precipitation-hardened stainless steel. Notch tensile test data indicate the material maintains notch ductility at temperatures down to –65 °F. Crack growth rate data indicate the material offers improved crack growth rate performance at temperatures down to –65 °F as compared to ambient temperature conditions. These data expand hardware design space with quantitative evidence of material capability at cold temperatures.

PRINCIPAL INVESTIGATOR: Preston McGill

PARTNERS: Aaron Adams, Alabama A&M University

FUNDING ORGANIZATION: Cooperative Agreement Notice

Computational Approaches to Understanding the Shape Memory of Ionic Polyimides for Additive Manufacturing

OBJECTIVE: *To determine the relationship between the molecular structure, physical properties, and performance of ionic polyimides, more specifically, of its shape memory behaviors.*

PROJECT GOAL/DESCRIPTION

Ionic liquids (ILs) utilizing anion exchanged with a non-nucleophilic anion, such as bistriflimide molecules, have received a significant amount of attention on account of their versatility, sustainability, and more importantly, their flexibility. ILs play a critical role in meeting modern spacecraft demands, such as 3D printing of instruments and tools for the International Space Station (ISS), while also holding out promise for new and improved polymers to impact our everyday lives. Hence, new strategies are needed to develop next-generation ILs based on more sustainable and low-cost materials. This project addresses the need for fundamental 'bench top' research on a customizable polymeric shape memory with 'tailor-made' properties potentially making it superior to the commercial blends offered in industry today.

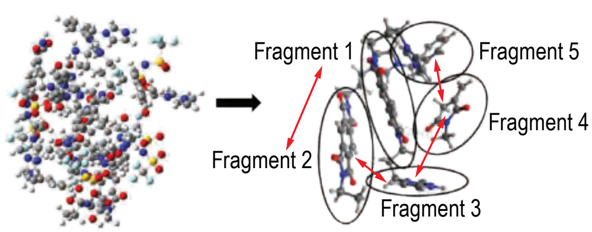


FIGURE 1. Example of studied IL polymer system.

APPROACH/INNOVATION

Our overall technical challenge is to use empirical potential classical molecular dynamics (MD) calculations on a high-performance computer (HPC) system for a long enough time (≈1 ms) to equilibrate structures that include explicit water and ions that would enable us to determine useful information about binding. In addition, a key issue that needs to be established is whether CHARM and/or Amber are providing qualitatively accurate information about the various polymers such that a correct picture of their flexibility is generated. Moreover, this force-field assessment activity can now be provided using electronic structure calculations based on the fragment molecular orbital (FMO) approach, as is provided in the GAMESS program, which allows for both molecular mechanics and molecular dynamics applications. Such calculations would be inconceivable for a whole polymer in past work, but our test calculations indicate that such calculations are now possible, which means that estimates of the errors that are made using the empirical force fields can be determined. In addition, before implementing the FMO method within GAMESS, we have done an extensive study using density functional theory-symmetry adapted perturbation theory (DFT-SAPT) to study the intermolecular energies of these polymers, the first study to date. A key milestone is that although DFT-SAPT and FMO are theoretically different, one being very expensive computationally (DFT-SAPT), the SAPT complexation energies deviate by 10 kcal/mol from the estimated FMO energies, which is an amazingly close result in view of the differing theoretical foundations. Furthermore, after publishing the work on DFT-SAPT and FMO approaches we will extend this work over the next year to look at large databases of ILs using machine learning and compare our work with experimentally published data.

RESULTS/ACCOMPLISHMENTS

The accuracy of the fragment molecular orbital method (FMO) was investigated using the pair interaction energy decomposition analysis (PIEDA). First, principles ab initio and energy decomposition analysis based on large-scale FMO calculations were used to obtain the interaction energies of two supramolecular complexes of polyimides broken down into fifteen fragments. Calculated interaction energies qualitatively explained the binding affinity shown in prior thermal analysis experimental results from previous summers. A comprehensive set of basis sets—STO-3G, 6-31G*, 6-311G*, 6-31++G**, aug-cc-pVDZ, and aug-cc-pVTZ—was employed along with Hartree Fock (HF) and Density Functional Theory (DFT) methods. In this report, we present only results using HF and the DFT LPBE0AC functional with the aug-cc-pVDZ basis set. Our results indicate the HF-calculated complexation energies agree qualitatively with the energetic ordering from LPBE0AC calculations with an aug-cc-pVDZ basis, both for structures dominated by hydrogen-bonding and π-π stacking interactions. When the PIEDA energies are decomposed into components, and we find that the electrostatic interactions dominate while induction and dispersion makes a significant contribution to the overall energy. Though this study is computational and uses much smaller systems, it was still possible to reproduce major trends observed in previously reported experimental studies. We have now extended this study to learn more about these systems employing Machine Learning (ML) and Data Science (DS). Toward this end, five students at Dillard University have been trained on computational chemistry and ML/DS. They have completed modules on Repositories and Data Management, Linear Regression and Neural Networks and Sequential Learning and Design of Experiments.

SUMMARY

We have isolated minimum energy structures for two PMDA API ortho xylene polymer orientations by means of simulated annealing molecular dynamics simulations in both vacuum and a high dielectric medium. We then use the FMO functional to study the total interaction energies, which are later broken into the electrostatic, dispersion, and induction contributions. The stacking and inter/intrabonded interactions were investigated and reported along with a comparison of HF and the DFT functional.

We learn that the folding in vacuum is primarily driven by Coulombic interactions among the charged species, naming ionic and rings and its counter ions. In fact, the presence of countering leads to an effective attraction between the stacking cyclic rings that accounts for roughly half the folding energy. In conclusion, we learn FMO PIEDA interaction energies scale well with high level ab intio calculations. Therefore, the functionalization of these materials chemical, conductive and mechanical properties may answer to the problem of additive manufacturing polymers.

PRINCIPAL INVESTIGATORS: Tomekia Simeon, Enrique M. Jackson

PARTNERS: Dillard University

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group, Technology Investment Plan

Utilizing Synthetic and In Situ-Generated Materials for Additive Manufacturing

OBJECTIVE: *To demonstrate viability high-performance (HP) ionic polymers and in situ generated materials in additive manufacturing and life support applications.*

PROJECT GOAL/DESCRIPTION

This projects utilizes the expertise, resources, and knowhow in the research groups of Professor Jason E. Bara (Department of Chemical and Biological Engineering) and Professor Paul A. Rupar (Department of Chemistry and Biochemistry) at the University of Alabama (UA) to support MSFC and advance important thrust areas relating to additive manufacturing and life support. The images below depict the use of Bosch carbon (supplied by MSFC) generated as a by-product of the Bosch process which converts carbon dioxide (CO_2) into water as a filler in silicones (left) and a coil made from a remarkable self-healing (SH), shape-memory (SM), thermoplastic elastomer with tunable properties/behaviors that is a candidate for 3D printing applications (right).

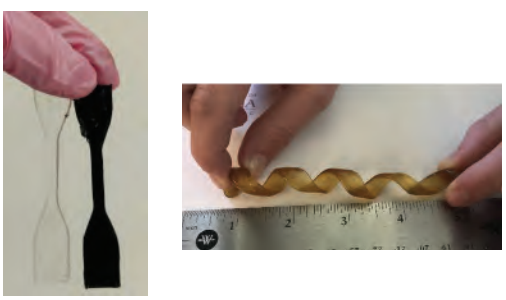


FIGURE 1. Bosch carbon (supplied by MSFC) generated as a by-product of the Bosch process which converts CO_2 into water as a filler in silicones (left) and a coil made from a remarkable self-healing (SH), shape-memory (SM), thermoplastic elastomer with tunable properties/behaviors that is a candidate for 3D printing applications (right).

APPROACH/INNOVATION

The first component of the work relates to the use of Bosch carbon in NASA's additive manufacturing (3D printing) efforts. Bosch carbon is a byproduct from the Bosch process, which is a technology under consideration for removing metabolic CO_2 from the atmosphere aboard the International Space Station. Bosch carbon is a black, graphitic powder and is considered a waste material. However, this work has shown that Bosch carbon can be extremely beneficial when used as a filler in thermoset polymers used for space-based additive manufacturing, thereby reducing the amount of polymeric material needed for space-based production of on-demand items and parts via 3D printing and/or conventional molding. This aspect of the project focused on determining the mechanical properties (e.g., tensile modulus) of silicones filled with Bosch carbon as a function of weight fraction and silicone type.

The second component focuses on the development of HP ionic polymers for 3D printing. A previous Cooperative Agreement Notice (CAN) project between MSFC and UA identified HP ionic polymers that have excellent processability, as well as extraordinary SH and SM properties. The current work has focused on scaling up the synthesis of HP ionic polymer as well as forming composites with ionic liquids (ILs), which are used as a means of modifying/controlling properties. The use of thermal analysis techniques (thermogravimetric analysis (TGA), differential scanning calorimetry (DSC)) is used to determine optimal processing conditions. A major advantage and distinguishing feature of these HP ionic polymers is that they are reusable many times without degradation, meaning that when a part is no longer needed, it can be broken down and fed to a 3D printer to make new parts.

This work is different than other work in materials for 3D printing in academia, industry, and government, as it utilizes intrinsically SH polymers, which require no special additives or techniques to achieve such behavior. The unique materials could be broadly utilized in a variety of industries/applications. The next steps in the work are to further demonstrate the viability of both types of materials in 3D printing. The follow on work will use a 3D bioplotter instrument to produce functional parts (e.g., O-rings, gaskets, PPE, etc.) and other objects that can benefit from the SM and SH properties. Furthermore, additional material formulations (i.e., polymer structures and composites with ionic liquids) will be developed to enhance mechanical properties (e.g., stronger, more elastic, faster healing).

RESULTS/ACCOMPLISHMENTS

The project generated a much deeper understanding of the properties of Bosch carbon silicone composites. Scanning electron microscope (SEM) images of Bosch carbon reveal long-aspect ratio rods, with a typical radius of these rods of ≈50 nm, with lattice fringes observed in transmission electron microscopy (TEM) micrographs, indicating the rods are graphitic in nature. Composites were formed with Bosch carbon loadings of 1–25 wt% in silicone. Increasing the loading of Bosch carbon improved the fracture-stress (the amount of force required to fracture the material) of the silicone polymer composites. Fracture-stress was further increased by reducing the particle size of the Bosch carbon. The primary lesson learned is the importance of processing/grinding the Bosch carbon to a consistent particle size. The project has demonstrated that HP ionic polymers can be safely synthesized at scales up to 1 kg without the need for any specialized equipment, which bodes well for much larger scale-up and use in both fused deposition modeling (FDM) 3D printing and conventional manufacturing processes (e.g, extrusion, injection molding, etc.). The thermal properties of the leading HP ionic polymers have been well-characterized, indicating a temperature of ≈150 °C is optimal for processing. The SH behavior has been shown to be extremely rapid with punctures of 5 mm able to fully close within 15 s. Cut pieces of the polymer have been demonstrated to fully heal and fuse within 1–3 hr. The tensile modulus of the leading HP ionic polymer has been measured as ≈2 MPa, and it is able to stretch up to 600% of its original length before breaking. Key lessons learned include processing techniques/conditions and identification of suppliers that will reduce the cost of material at scale.

SUMMARY

The CAN agreement between MSFC and UA has been extremely productive in terms of advancing these unique materials for 3D printing applications. The use of intrinsically SH and SM polymers within FDM 3D printing is groundbreaking and holds great promise for future application in both in-space and terrestrial manufacturing. The project also demonstrates that Bosch carbon is viable for use as a filler in thermosetting polymers.

PRINCIPAL INVESTIGATORS: Jason E. Bara, (Chemical and Biological Engineering, University of Alabama), Enrique M. Jackson (MSFC)

PARTNERS: University of Alabama

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group, Technology Investment Plan

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

OBJECTIVE: *To reduce design and assembly schedules while allowing for reduced parts, increased reliability, and significant weight reduction; creating a healthy American supply chain for large-scale, regeneratively-cooled liquid rocket engines.*

PROJECT GOAL/DESCRIPTION

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is developing and advancing large-scale and lightweight regeneratively-cooled liquid rocket engine components utilizing multi-metallic freeform additive manufacturing (AM) and composite overwrap techniques and advancing AM analysis capabilities. All of these technologies combined are being implemented to significantly reduce design and fabrication cycles. RAMPT is reducing the design, fabrication, and assembly schedules while allowing for reduced parts, increased reliability, and significant weight reduction, and is creating a healthy American supply chain.

The three primary goals of the RAMPT project are:

(1) Develop additive and advanced manufacturing methods and design processes that enable new regeneratively cooled thrust chamber assembly technology focused on a large scale.

(2) Identify and optimize AM design and fabrication processes that lead to reduced production lead times and analysis life cycle for large-scale thrust chamber assemblies.

(3) Engage manufacturing community organizations in the development effort and facilitate infusion of technology into the commercial industry.

APPROACH/INNOVATION

The RAMPT project is focusing on advancing the following technical areas:

(1) Laser powder directed energy deposition (LP-DED) freeform AM techniques to fabricate an integrated, regeneratively cooled channel wall nozzle structure.

(2) Composite overwrap techniques to significantly reduce weight and provide structural capability for a large thrust chamber assembly (TCA).

(3) Bimetallic and multi-metallic AM and deposition techniques, including copper-alloy-to-superalloy transitions to optimize material performance.

(4) Advanced modeling and simulations of large-scale deposition techniques to obtain optimal property predictions and material designs and to develop 'smart' tool-paths to reduce distortion and provide acceptable components.

(5) Integrated, regen-cooled combustion chamber and nozzle design tool to significantly reduce design cycles and take full advantage of additive technologies.

NASA has engaged Auburn University under contract to develop and operate the RAMPT public-private partnership with over eleven specialty manufacturing vendors to enable a long-term supply chain available to the government and the commercial rocket industry.

RESULTS/ACCOMPLISHMENTS

The RAMPT project is maturing the manufacturing technologies and integration of various scales of hardware. This allows for early lessons to be learned on subscale hardware while progressing towards larger-scale where increasing chamber pressures as thermal and structural loads become more challeng-

FIGURE 1. 2,000-lbf thrust-class coupled hardware.

ing. Early hot-fire testing was completed on 2,000-lbf thrust-class decoupled hardware, which included composite overwrap chambers and a laser powder directed energy deposition (LP-DED) nozzle with integral channels. This demonstrated feasibility with temperatures approaching 240 °F on the composite overwrap. Decoupled hardware has been developed for the 7,000-lbf and 40,000-lbf thrust-classes and will complete hot-fire testing in FY 2021.

Selection of composite material systems and winding/overwrapping strategies for the 7,000-lbf and 40,000-lbf thrust class hardware is continuing under RAMPT. In addition, bimetallic AM material characterization studies are underway to compare gas cold spray, LP-DED, and laser hot wire DED cladding techniques for manifolds, structural jackets, and coupled chambers/nozzles. These techniques all have different advantages and disadvantages including heat input and potential for distortion, ability to deposit on complex surfaces, material overspray/usage, bonding strength, supply chain, and feedstock availability.

Another objective of the RAMPT project is to demonstrate the scale of the LP-DED process for integral channel nozzles, which is being completed through a series of manufacturing demonstrators and test hardware. The RAMPT team used the BP-DED technique to produce one of the largest nozzles NASA has printed, measuring 40 in in diameter and standing 38 in tall, with fully integrated cooling channels. This nozzle was fabricated in record time—just 30 days compared with nearly one-year using traditional welding methods. Additional development work is required at larger scale, which NASA is currently working with industry partners under supplemental funding through the NASA Space Launch System (SLS) program.

FIGURE 2. NASA HR-1 Nozzle with three channel transitions (40-in diameter).

Simulation modeling has been advanced to inform build strategies that control distortion during fabrication. As part of this development, computational modeling and validation to predict residual stresses and distortion in additive parts were compared across multiple simulation codes. Many of these simulations are limited to monolithic materials, although bimetallic is being studied. The bimetallic modeling will require additional future development efforts to fully evolve.

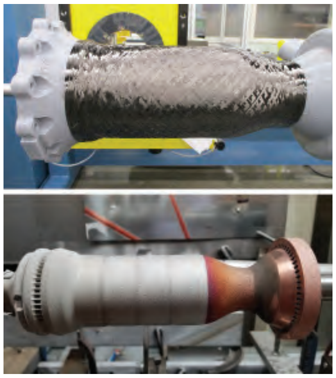


FIGURE 3. Composite Overwrap and Coldspray Bimetallic Additive Processes.

SUMMARY

RAMPT impacts all phases of the engine TCA life cycle by addressing the longest lead, highest cost, and heaviest component in regeneratively-cooled rocket engines. The LP-DED process has completed a series of manufacturing demonstrators and test hardware, various composite overwrap chamber configurations are in development, bimetallic technology is advancing, and computation modeling is helping inform decisions along the way.

PRINCIPAL INVESTIGATORS: Paul Gradl, Chris Protz

PROJECT MANAGER: John Fikes

PARTNERS: Auburn University

FUNDING ORGANIZATION: Space Technology Mission Directorate, Game Change Development

FOR MORE INFORMATION: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/RAMPT/

Viability Assessment of Printed Powerless Sensor Structures for Aerospace Environment

OBJECTIVE: *To examine the feasibility of using 3D-printed-based carbon fiber composites with embedded triboluminescent optical fiber (ITOF) sensor for structural health monitoring of aerospace vehicles.*

PROJECT GOAL/DESCRIPTION

This project focuses on addressing NASA's demand for efficient, robust, and reliable embedded sensors for structural health monitoring of aerospace vehicle structures. The sensor should possess increased performance, environmental durability, reduced mass, power consumption, and size. The Florida A&M University team proposed to design and develop a novel high-performance powerless optical fiber sensor that integrates the physical principles of mechanoluminescence (i.e., triboluminescent) materials. The in situ ITOF will be embedded in a 3D printed carbon fiber composite, and its viability for load and damage detection will be assessed.

APPROACH/INNOVATION

This work investigates additive manufacturing technologies and viability assessment of printed powerless sensor structures for the aerospace environment. Phase 1 of the project relates to 3D printing ITOF sensors for structural health monitoring. Phase 2 of the project will evaluate the performance of the printed sensor under environmental conditions (i.e., near-space). Additive manufacturing is a transformative approach to industrial production that enables the creation of lighter, stronger parts and systems. The 3D-printed, embedded powerless ITOF sensor structures can help address MSFC's need for sensors with reduced mass, increased performance, and improve the capability to detect, characterize, and track space objects.

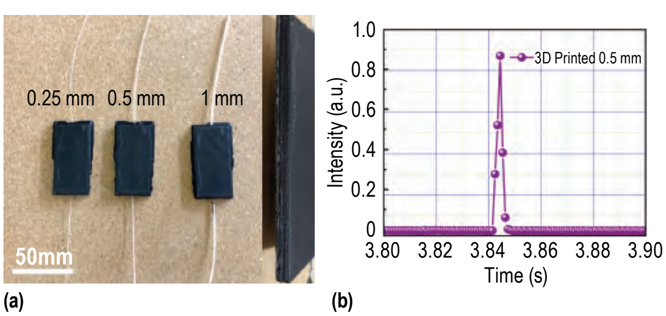


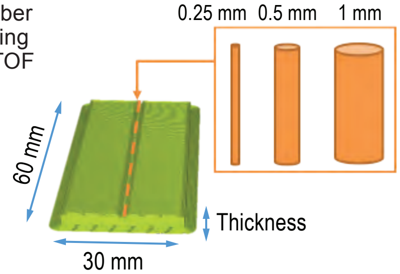
FIGURE 1. (a) Embedded ITOF sensors in a 3D-printed chopped carbon fiber ABS matrix and (b) results of the impact test for 0.5 mm size ITOF sensor.

RESEARCH PLAN

The research plan was to:

- Replicate current ITOF sensor and test for effectiveness.
- Investigate the behavior of the 3D-printed embedded ITOF sensors.
- Study the parasitic effects of the embedded ITOF sensor on the structural integrity of the composite.
- Perform tensile and flexural tests in ambient conditions to characterize behavior.
- Explore the survivability of powerless sensors in the aerospace environment and the behavior of the ITOF sensors at the temperature range of –120 to 150 °C.
- Conduct mechanical tests, such as (1) three-point bend; (2) double-cantilever beam; and (3) Dynamic Mechanical Analysis (DMA) to be carried out at extreme conditions (–150 °C), while signals from embedded ITOF sensors are simultaneously collected to evaluate the performance of the structural health monitoring systems; and (4) medium- to high-velocity impact tests will be performed by railgun (at MSFC) to simulate the impact of projectiles at velocities exceeding the speed of sound in-space environment.

FIGURE 2. Chopped carbon fiber composite in ABS matrix showing mid print for the laying of the ITOF sensors with different sizes.



KEY CHALLENGES

The key challenges were poor interface bonding of the 3D-printed, embedded ITOF sensors and obtaining comparable 3D-printed carbon fiber parameters (e.g., thickness, material quality) with the vacuum assisted resin transfer molding (VARTM) process.

MILESTONES OR DELIVERABLES FOR FY 2020:

Milestones or deliverables for FY 2020 included:

- Manufacturing ITOF sensors using in-house. dip-coating machine.
- Manufactured embedded ITOF sensor system.
- 3D-printed chopped carbon fiber in acrylonitrile-butadiene-styrene (ABS) matrix with embedded itof sensors.
- Results and evaluation of the sensor systems.
- Designed printhead for direct extrusion of optical fiber coated triboluminescence.

The proposed project will create a paradigm shift in industry, academia or government as it combines two distinct innovative ideas, which are ‘powerless sensing’ and ‘additive manufacturing.’ The synergy between powerless sensing and additive manufacturing will result in a robust, efficient, and reliable sensor system with commercialization potential and trigger pathways for more research opportunities in embedded sensors.

RESULTS/ACCOMPLISHMENTS

- The dip coating machine was revamped and calibrated.
- ITOF sensors of different optical sizes (0.25, 0.50, 1 mm) were manufactured.
- The efficacy of the ITOF sensors was assessed using the impact test approach. The results of the embedded composite sensor systems showed consistent and repeatable responses upon impact energy of 10 J.
- 3D-printed and tested embedded ITOF sensors of different optical fiber sizes in chopped carbon fiber in the ABS matrix (figure 1a). The printing parameters are 0.4 mm nozzle, 0.2-mm layer height at 220 °C.
- The sensors produced distinct and clear signals upon impact (see figure 1b). It is important to note that the carbon fiber in the ABS matrix was used just for a preliminary study. Subsequently, the team intends to use a more resilient carbon fiber material to substantiate the impact test results and other proposed mechanical tests.

SUMMARY

In summary, we revamped the traditional method of manufacturing embedded ITOF sensor system. The sensor system showed repeatable and reproducible responses to the impact test. Next, we began investigations on the 3D-printed embedded sensor systems. Several batches of chopped carbon fiber ABS matrix with the embedded ITOF sensors were printed and assessed. The 3D-printed sensor systems were subjected to impact tests, and their results were collected. The preliminary results suggest that the 3D printed systems are viable, although further enhancements are necessary. In order to advance our studies, we aim to continue improving on the 3D-printing process by optimizing the printing materials, parameters, and conditions.

PRINCIPAL INVESTIGATORS: Okenwa Okoli, Enrique M. Jackson

PARTNERS: Florida A&M University

FUNDING ORGANIZATION: Cooperative Agreement Notice

In-Space Manufacturing (ISM)

OBJECTIVE: *To develop and enable the technologies, materials, and processes required to provide affordable, sustainable on-demand manufacturing, recycling, and repair during exploration missions.*

PROJECT GOAL/DESCRIPTION

The In-Space Manufacturing (ISM) portfolio provides a solution towards sustainable, flexible missions through on-demand fabrication, replacement, and recycling capabilities to support critical systems, habitats, mission logistics, and maintenance. These capabilities can provide tangible cost savings by reducing launch mass, reducing risk by decreasing dependence on spares, enabling design systems for maintainability, and enabling crew to respond to unanticipated scenarios.

FIGURE 1. ISM logo.

APPROACH/INNOVATION

The current International Space Station (ISS) logistics model is heavily dependent upon Orbital Replacement Units (ORUs) for system-based repair and maintenance. Logistics support is a significant challenge for extended human operations in space, especially for missions beyond low Earth orbit (LEO) where timely resupply or abort in the event of emergency would not be possible.

The ISM portfolio includes three projects funded by the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program: (1) on-demand manufacturing of metals (ODMM), (2) on-demand manufacturing of electronics (ODME), and (3) and recycling and reuse (RnR). These three projects will significantly reduce mission risk and logistical requirements while enabling Earth-independent human spaceflight. Capabilities are being developed by leveraging new terrestrial technologies and adapting them for operations in pressurized, reduced, or microgravity environments. The ISS serves currently as a one-of-a-kind test bed on the ISM technology development roadmap.

RESULTS/ACCOMPLISHMENTS

ON-DEMAND MANUFACTURING OF METALS

The ODMM project is pursuing the commercial development of hybrid (additive-subtractive) manufacturing prototype units for demonstration aboard the ISS. Two distinct approaches are being considered. Techshot, Inc., has developed a fully integrated ground-based prototype system using bound metal deposition (BMD), known as the Fabrication Laboratory, or FabLab, which can presently produce titanium alloy parts. Made in Space, Inc., is developing a wire-arc additive manufacturing (WAAM) system called Vulcan to produce aluminum and/or titanium alloy parts (only a single metal material will be demonstrated during flight operations). Both approaches have the potential to expand material processing capabilities to other metals as well as polymers, with the vision of providing a multi-material capability for future missions.

During the final part of the Phase A FabLab project, Techshot completed a preliminary design review, completed and demonstrated their prototype FabLab hardware by successfully manufacturing five ‘challenge build’ parts specified by NASA (these parts represent candidates for on-demand manufacturing on space missions), and delivered their Phase A final report on their two-year development effort. Currently, the ISM project and Techshot are in discussions with

FIGURE 2. Cross-section of AstroSense printed sensor.

the ISS Research Office to continue progress of their FabLab concept for potential demonstration aboard ISS.

The Vulcan effort from Made in Space focused on demonstrating subsystems and building out an engineering development unit, which integrates multiple heads for metal 3D printing, polymer 3D printing, and subtractive manufacturing. Made in Space successfully demonstrated the following subsystems for Vulcan: the weldhead for WAAM polymer 3D printing, subtractive manufacturing, automated machine tool changeout, an environmental control unit for chip capture, an in-process monitoring system to assess weld quality following deposition of a layer, and an iris clamp and robotic gripper for part fixturing and machining.

ON-DEMAND MANUFACTURING OF ELECTRONICS (ODME)

The ODME project is developing a new wireless wearable sensor device for astronaut crew health, called AstroSense, using deposition processes intended for eventual demonstration on ISS. This novel, next-generation device will sense environmental conditions and astronaut cortisol response (an indicator of stress).

The ODME project is also developing leading-edge technologies for harvesting and storing energy for electronics and sensor networks that can one day be demonstrated in space. ODME is working with a number of universities on these innovative technologies, which include a printed antenna array to harvest power from radio frequency identification (RFID) or WiFi electromagnetic networks, a printed thermoelectric device that will harvest power from small temperature differences in space environments, and several printed supercapacitor technologies to store the energy harvested by the above methods and use it for electronic circuits and sensor networks.

In addition to developing a cortisol biosensor to monitor astronaut stress, ODME is also working with the Stanford Linear Accelerator Center (SLAC) team as part of their COVID-19 Response Program to develop a silicon chip capable of detecting the SARS-CoV-2 antigen that can be produced inexpensively in high volumes.

RECYCLING AND REUSE (RNR)

Multiple waste streams that are not conducive to long-duration missions exist in the current ISS logistics model. The RnR project is focused on recycling and reusing packaging materials, such as films and foams, due to their ubiquity and the large volume needed for stowage. Previous efforts under an SBIR with Cornerstone Research Group (CRG) evaluated a limited subset of existing launch packaging materials. In early 2020, an in-house team consisting of polymer experts from MSFC's Materials and Processes Laboratory expanded the evaluation of existing packaging materials to include the 101 polymers listed in the Cargo Missions Manifest. Following this analysis, which took into account the impact of viscosity, material form, safety concerns, and thermal properties on printing and recycling, the team concluded that none of these materials were high-potential candidates worthy of further investigation. Instead, it was recommended that materials be developed with the intention of being recycled. This analysis will inform future efforts within the RnR project.

The Regolith ISS Technology Demonstration (RegISS) project, part of RnR, will 3D print a mixture of lunar regolith simulant and a thermoplastic material in the microgravity environment of the International Space Station. The RegISS proof-of-concept shows the viability of printing with regolith composite material in a reduced gravity environment; it is a fundamental example of in situ resource utilization and is applicable to lunar and Martian surface missions (Artemis and Moon to Mars). Partnering with Made In Space (MIS), the effort will modify a version of the commercially available Additive Manufacturing Facility (AMF) and will fly to ISS in 2021.

SUMMARY

The In-Space Manufacturing portfolio of ODMM, ODME, and RnR is actively developing technology demonstration experiments to be flown on the ISS within the next 4 years. These experiments will be some of first steps in the manufacturing methodologies to be used on the Moon, Mars, and deep-space exploration missions of the future.

PROJECT MANAGER: Phil Hall

PARTNERS: Techshot, Inc.; Made In Space, Inc.; Tethers Unlimited, Inc.;

FUNDING ORGANIZATIONS: Space Technology Mission Directorate, Game Changing Development, and Human Exploration; Operations Directorate Advanced Exploration Systems Division

Polymer Coatings with Glass Bubbles for Thermal Radiation Control in Space

OBJECTIVE: *To develop lightweight and flexible polymer composite coatings for thermal radiation control in space by integrating hierarchical hollow glass microspheres and surface texture.*

PROJECT GOAL/DESCRIPTION

The goal of this project is to develop lightweight and flexible polymer-based selective emitter materials for thermal radiation control in space by integrating hollow glass microspheres, or glass bubbles, which introduce a high degree of structural hierarchy, as well as pyramidal surface structure to enhance optical control (figure 1). Glass bubbles allow substantially lower weight and larger interface density compared to other designs using solid spheres, and the large interface density is important for selective optical control. Polymers such as polydimethylsiloxane (PDMS) not only provide flexibility but are also compatible with a cast molding process to create surface texture that can provide further optical control.

APPROACH/INNOVATION

The project will prepare the samples by integrating a controlled volume fraction of microscale glass bubbles from 3M™ within PDMS made by mixing commercially available silicone elastomer and curing agent. After stirring and degassing, the PDMS film will be applied to a textured mold and put into a vacuum oven for heated-drying. After a full dry, the PDMS film will be peeled off from the mold. Following sample preparation, the optical properties will be characterized by ultraviolet-visible-near infrared (UV-VIS-NIR) spectroscopy in wavelengths of 0.4–2.5 µm and Fourier-transform-infrared (FTIR) spectroscopy in wavelengths of 2.5–16 µm. The emissivity results will be compared with the spectral emissivity (in the 7.5–14 µm wavelength region) from rigorous coupled-wave analysis (RCWA) and finite-difference time-domain (FDTD) method. The computational results will also be validated by testing thermal control performance in the ambient environment and at various conditions.

The project will also use Mie theory and FDTD computations to investigate and understand the driving mechanism for optical properties of solar reflectors or selective emitters composed of hollow microspheres with uniform and varying diameters. Surface texture effect on optical properties will be investigated using RCWA and FDTD simulations. The geometric parameters for these surface structures, mainly the aspect ratio (height/pitch), will be varied to optimize the current design.

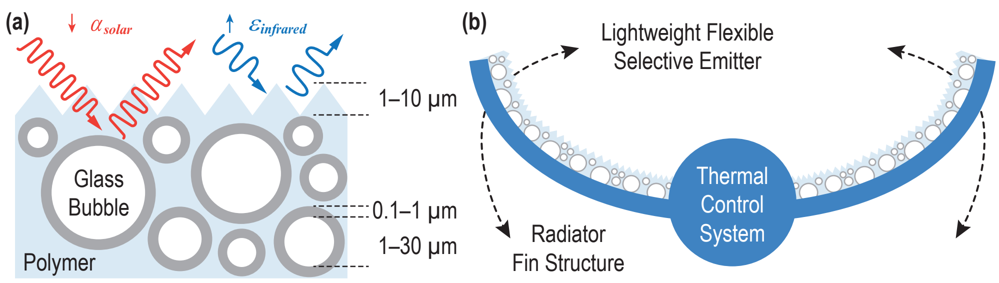


FIGURE 1. Proposed material and concept system designs: (a) The controlled morphology of glass bubbles within a polymer film; (b) the lightweight flexible selective emitter could be integrated with radiator fin or inflatable habitat structures and enable breakthroughs in thermal control of deployable and flexible systems.

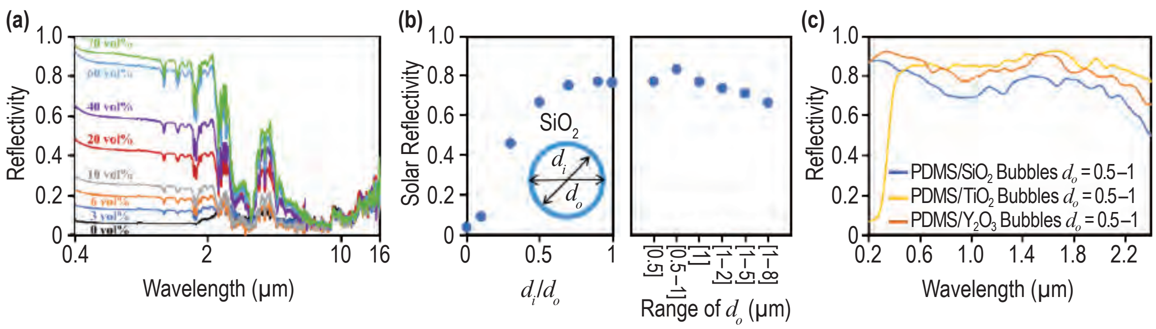


FIGURE 2. Experimental and computational reflectivity of polymer coatings with hollow microsphere design: (a) experimentally measured reflectivity of polymer coatings with varying volume factions of glass bubbles in PDMS; (b) FDTD simulated reflectivity in the solar region for hollow SiO_2 microspheres with different shell thicknesses and diameters; (c) FDTD simulated reflectivity in the solar region of bubbles made of SiO_2, titanium dioxide (TiO_2) and Y_2O_3 with the same diameter distributions.

RESULTS/ACCOMPLISHMENTS

We have prepared lightweight, low-cost, and scalable white polymer coatings with a controlled volume fraction of glass bubbles within a PDMS film. As the volume fraction increases from 0% to 70%, the average reflectivity in the visible region and NIR region is enhanced from 0.14 to 0.94 and from 0.13 to 0.84, respectively (figure 2a). The outdoor temperature measurements against a white background show that our cool white polymer coating achieves a 3 °C subambient cooling. The measurements against a black background show that the polymer coating cools the black background up to 20 °C.

We have studied the solar reflectivity in the 0.4–2.4 μm wavelength range of solid and hollow microspheres with the diameter varying from 0.125 to 8 μm using Mie theory and FDTD simulations. Our analysis has shown that hollow silicon dioxide (SiO_2) microspheres with a thinner shell are more effective in scattering light, compared to solid microspheres. When the diameter is uniform, 0.75 μm SiO_2 hollow microspheres provide the largest solar reflectivity of 0.81. When the diameter is varying, the random-distributed 0.5–1 μm SiO_2 hollow microspheres provide the largest solar reflectivity of 0.84 (figure 2b). The effect of varying diameter is further supported by the backscattering ratio, where hollow SiO_2 microspheres with 0.5–1 μm diameters achieve the strongest backscattering among all studied designs. Based on our investigations using FDTD, we have identified that materials with a low extinction coefficient is preferable, and yttrium oxide (Y_2O_3) hollow microspheres are the most promising candidate due to the high average reflectivity across the solar wavelength range (figure 2c).

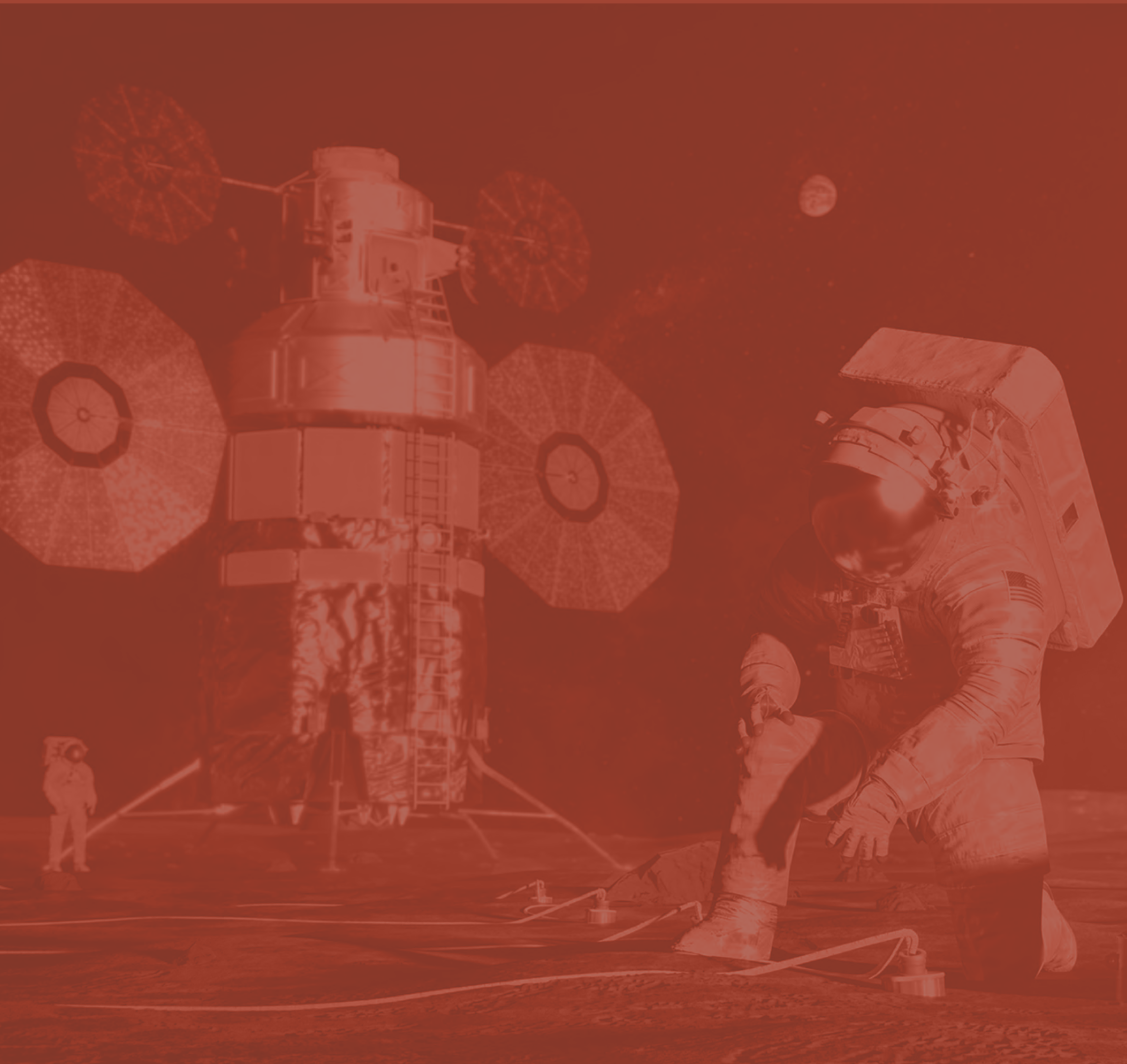
SUMMARY

In this project period, we have successfully prepared lightweight, low-cost, and scalable polymer coatings for thermal radiation control by integrating 70% volume fraction of glass bubbles within a PDMS film, and the polymer coatings demonstrate unique properties that include a high solar reflectivity of 0.92 and high mid-IR emissivity of 0.85. The measurement results suggest that the polymer coatings can achieve a subambient cooling and reduce the temperature significantly for black background. We have also studied the solar reflectivity of solid and hollow microspheres within a PDMS matrix using Mie theory and FDTD simulation method. The result shows that hollow microspheres with a thinner shell are more effective in scattering light and lead to a higher solar reflectivity. The high scattering efficiency, owing to the refractive-index contrast and large interface density, in hollow microspheres allows low-refractive-index materials such as SiO_2 to have a high solar reflectivity of 0.77, when the thickness of the film is 100 µm. We have also found that the random-distributed 0.5–1 µm SiO_2 hollow microspheres provide the largest solar reflectivity of 0.84 among all studied designs and the effect of varying diameters is supported by the backscattering ratio. We have also identified that materials with a low extinction coefficient in the solar spectrum, such as Y_2O_3, are promising to achieve a high solar reflectivity when combined with the hierarchical hollow microspheres design.

PRINCIPAL INVESTIGATORS: Jaeho Lee (University of California, Irvine), Enrique M. Jackson (MSFC)

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group, Technology Investment Plan

TECHNOLOGY AREA 14:
Thermal Management Systems



Lunar TheRMiS: Lunar Thermal Regulation for Mission Sustainability

OBJECTIVE: *To design thermal control solutions that will enable extended science and exploration by allowing robotic landers to survive the lunar night.*

PROJECT GOAL/DESCRIPTION

In recent years, there has been a push to return a human presence to the Moon, with an increased focus on sustainability. Part of this sustainability will be reusable and long-duration vehicles, as Apollo-style, single-use vehicles are too expensive and impractical. Numerous engineering challenges exist when developing such vehicles, one of which is designing a thermal control system (TCS) that can survive the extreme cold of the lunar night. Currently, the state of the art is to use radioisotope heating; however, this is difficult to sustain. Nuclear material has large cost, sociopolitical concerns, and integration challenges, making its use impractical for many missions. The Lunar Thermal Regulation for Mission Sustainability (TheRMiS) team is developing an advanced TCS solution using non-nuclear components that will allow a 50–500 kg class lander to survive the lunar night. This capability will enable scientific missions to close lunar human exploration strategic knowledge gaps as well as enable sustainable lunar presence architectures that depend on survivability through the lunar night. The team is collaborating with Astrobotic, an innovator in commercial lunar landers, who will be providing their Peregrine lander as a testbed for analysis and eventual flights to the Moon. This effort will advance the TCS technology through system-level thermal vacuum testing and culminate in the delivery of flight ready hardware to Astrobotic, for a demonstration of the system during their second mission to the Moon. In addition, the effort will result in a validated toolbox of thermal modeling techniques that can provide a set of TCS solutions for broad application to lunar landers as well future thermal challenges faced by NASA and its commercial partners.

FIGURE 1.
Lunar TheRMis logo.

APPROACH/INNOVATION

To solve this problem, the Lunar TheRMiS team is leveraging individual thermal control technologies—both heritage components technology readiness level (TRL) 9, as well as advanced, mid-TRL (4–6) components—to develop an innovative non-nuclear solution. The team is utilizing advanced thermal control hardware such as variable conductance heat pipes (VCHPs), loop heat pipes (LHPs), embedded heat pipe plates (EHPPs), thermoelectric coolers (TECs), phase change materials (PCMs), thermal switches, and the like; each has their own unique characteristics that allow them to solve pieces of the puzzle. It is important to point out that a TCS for the lunar night/day is a complicated system with complex interactions between the thermal control devices. It is unlikely that an integration of all commercial-off-the-shelf (COTS) hardware will be sufficient. This is driving the need for the combination and optimization of a TCS comprised of both heritage COTS as well as advanced, mid-TRL components. The challenge here is leveraging the strengths (and weaknesses) of each technology, while balancing the combination of heritage and next generation components to advance the TCS technology as a whole towards the lunar night solution.

To complete Objective 1, the team created a matrix of thermal control options, categorizing them by type and sorting by TRL. These options were qualitatively compared to highlight their strengths and weaknesses with regard to surviving the lunar night. In Objective 2, Potential solutions will be crafted from the matrix produced in Objective 1, with prototyping and testing to further narrow and mature to TRL 6. Lastly, Objective 3 will produce a flight demonstration unit that will be integrated and delivered to Astrobotic for TRL 7 technology demonstration on the lunar surface. The solution space defined by the proposed TCS as well as the model validation and verification will be useful to the greater NASA and commercial community, as it provides a toolset for successfully implementing advanced TCS designs onto a broad range of lunar missions and beyond.

RESULTS/ACCOMPLISHMENTS

During the past year, the Lunar TheRMiS team was focused on the creation of a methodology document that will serve as a baseline for designing a thermal control system to survive the lunar night. Part of this methodology document is the technology matrix that highlights the strengths and weaknesses of multiple advanced thermal control devices. These technologies will be tested as part of Objective 2, which was also intended to be performed in 2020. This testing was unable to be performed due to work from home orders starting in March. Approval was received to begin testing in November 2020. A parametric trade study is also underway to better understand the interactions of different thermal technologies when applied to a lander system. The sensitivities of said systems need to be understood to determine if any small changes can produce large impacts in component temperatures or power requirements.

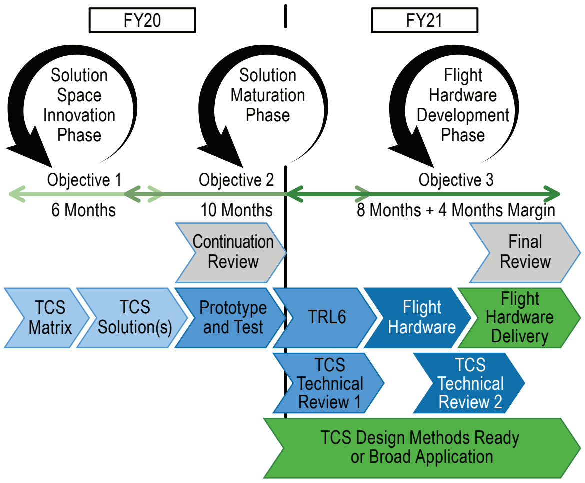


FIGURE 2. Lunar TheRMis objectives.

SUMMARY

Lunar TheRMiS is developing a thermal control solution to survive the lunar night. This technology is being applied to robotic lunar landers with a future goal of applying to robotic rovers as well. Developing this capability is crucial to further exploration and scientific output on the lunar surface. The team has spent time collecting a matrix of advanced thermal control technologies that will be analyzed and tested on the path to a complete solution. This solution is being developed in collaboration with Astrobotic and their Peregrine lander, which will be flying Lunar TheRMiS demonstration technologies to the lunar surface over the next few years.

PRINCIPAL INVESTIGATOR: William Johnson

PARTNERS: Astrobotic

FUNDING ORGANIZATION: Space Technology Mission Directorate

High-Efficiency Thermal Switch for Extreme Variable Space Exploration Environment

OBJECTIVE: *To design, build, test, and qualify an ultra-high efficiency thermal switch to enable continuous, long duration operation in vacuum and nonvacuum extreme thermal conditions encountered on the lunar surface, Mars surface, and on deep space missions.*

PROJECT GOAL/DESCRIPTION

NASA MSFC and Jet Propulsion Laboratory (JPL) are collaborating to design, build, and test a high-efficiency thermal switch. JPL is designing, fabricating, and performing functional testing on the thermal switch prototype; and MSFC is assisting in developing and conducting vibration and thermal vacuum testing in relevant conditions to assess the operability of the switch and qualify the technology for use in future exploration and science missions. A thermal switch modulates the thermal contact between a component and a radiator surface. When the component temperature increases, a contact is made between the instrument and a radiator to transfer heat from the hot component to the radiator to be dissipated. When the component temperature decreases, the contact is broken, reducing the heat transferred from the component to the radiator. The switch is considered 'on' when the strong thermal contact is created and 'off' when the strong contact is broken. This variable heat transfer is crucial to enabling components to survive both extreme hot and extreme cold temperatures present in some space environments, such as the lunar surface. Figure 1 shows the extreme varying temperatures of the lunar surface through data collected by the Lunar Reconnaissance Orbiter (LRO) Diviner instrument. The thermal switch qualified will contribute to addressing the need to regulate temperatures across both extreme hot and extreme cold environments with a higher turndown ratio (on/off conductance).

APPROACH/INNOVATION

This high-efficiency switch uses materials with both positive and negative coefficients of thermal expansion (CTE) arranged in stages to increase the differential thermal expansion. This will create a larger gap between interfaces when off, which further reduces the off thermal contact and increases the turndown ratio in environments with atmosphere, such as on Mars. This switch is unique because it will be effective both in vacuum and in nonvacuum.

A key technical challenge has been exploring the positive and negative CTE materials to use in the switch and combining the two together in a cohesive assembly. JPL has succeeded in selecting the appropriate materials and building the prototype during the 2020 development effort. The developed switch is complimentary to existing thermal switches in that it offers a variable conductance heat transfer path, but it is different because it uses both positive and negative CTE materials, which creates a larger differential thermal expansion and a larger turndown ratio.

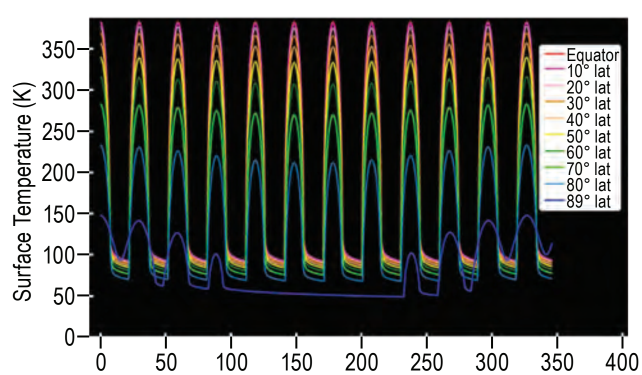


FIGURE 1. LRO Diviner data showing Lunar surface temperatures.
(Courtesy: https://www.diviner.ucla.edu/science).

A high turndown ratio in thermal technology is essential for surviving extreme varying thermal environments because it is required to provide a path to radiate excess heat when hot, yet insulate and conserve heat when cold. The higher the turndown ratio, the more power and mass can be saved by reducing heater power requirements and radiator surface area needed, which will enable greater science return on missions. It could also prevent the need to hibernate during extreme cold conditions, which would also enable further science data to be collected.

RESULTS/ACCOMPLISHMENTS

JPL has succeeded in exploring the positive and negative CTE materials to use in the thermal switch and has developed a strategy in assembling the materials into a cohesive and compact design that will enable the switch to be on when the strong thermal contact is enabled and off when the thermal contact is broken. A prototype switch has been designed and built as planned, but due to mandatory telework and restrictions on lab use during the COVID-19 pandemic, much of the proposed testing has been delayed. The anticipated work in FY 2021 includes the preliminary testing at JPL and the full range of vibration and thermal vacuum testing at MSFC. Following the completed testing, a verified turndown ratio will be determined, and the switch can be incorporated into lunar science and other missions to maintain temperatures of electronic components to enable further science and increase efficiency. A model of the prototype is shown in figure 2.

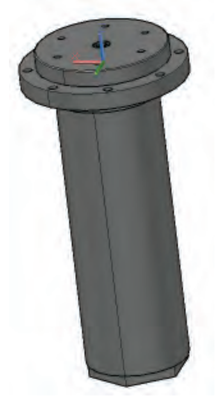


FIGURE 2. Model of switch.

SUMMARY

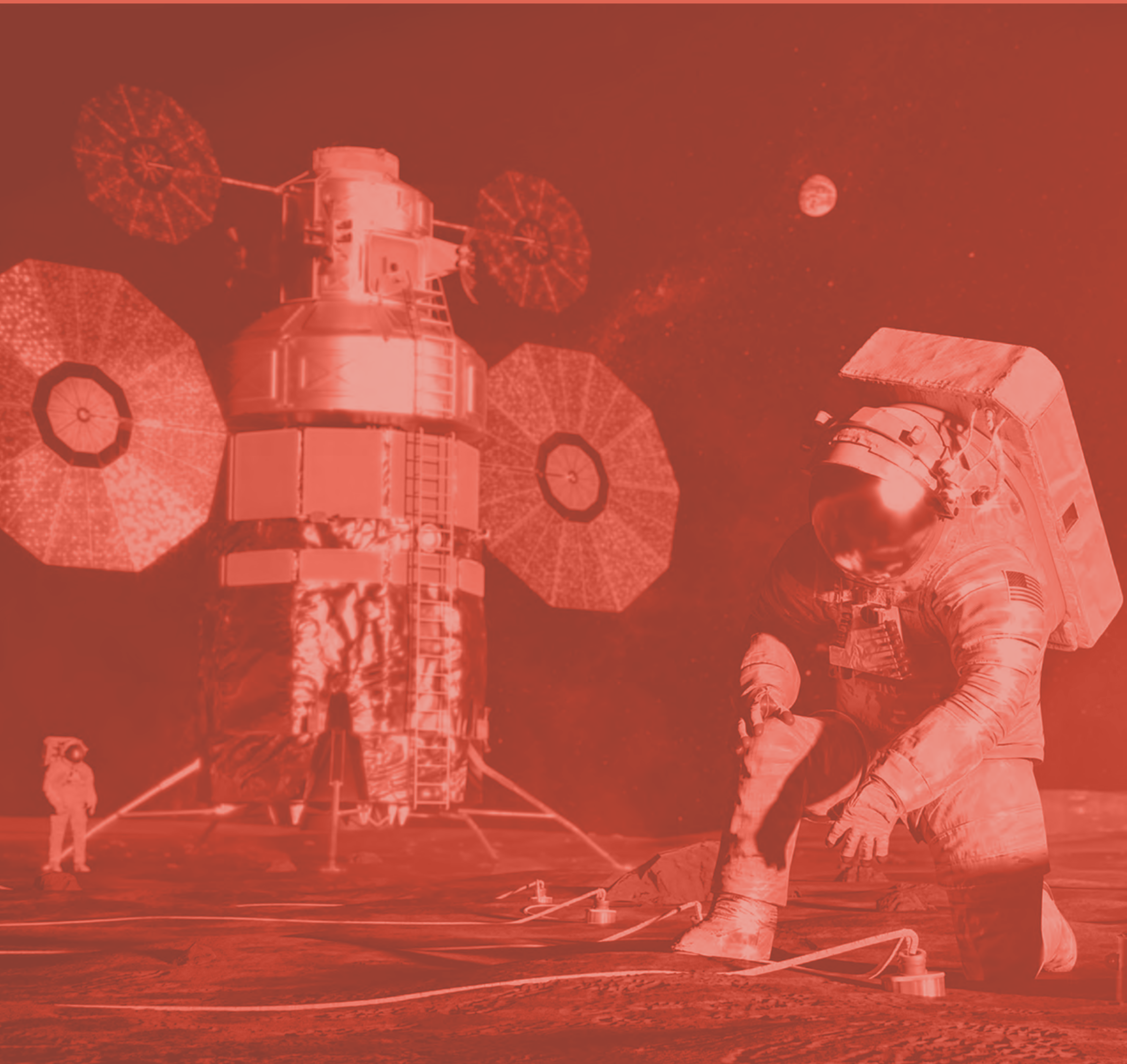
JPL and MSFC are collaborating to design, build, test, and qualify a high-efficiency thermal switch to enable continuous, long-duration operation in vacuum and nonvacuum extreme conditions encountered on the lunar surface, Mars surface, and deep space missions. The variable heat transfer path created by the thermal switch is essential to enabling the survival of components in both extreme hot and extreme cold environmental conditions. The technology is unique because it uses both positive and negative CTE material in stages to create a larger gap in the off state, which increases the total turndown ratio and enables to switch for use in nonvacuum in addition to use in vacuum. JPL has succeeded in designing and building a prototype of the proposed switch. Upcoming work includes functional testing at JPL and vibration and thermal vacuum testing in relevant conditions to qualify the technology for use at MSFC. The work completed at the time of this report has raised the technology readiness level (TRL) from a 2 to a 3, and by the end of environmental testing at MSFC, will achieve a TRL of 5 and 6 for some environments.

PRINCIPAL INVESTIGATOR: Stephanie Mauro

PARTNERS: Dave Bugby, Jose Rivera (Jet Propulsion Laboratory)

FUNDING ORGANIZATION: Center Innovation Fund

TECHNOLOGY AREA 17:
Guidance, Navigation, and Control



Correlated Electromagnetic Levitation Actuator (CELA)

OBJECTIVE: *To redefine the future of attitude control systems.*

PROJECT GOAL/DESCRIPTION

Correlated electromagnetic (CE) levitation actuator (CELA), is a frictionless reaction sphere addressing deficiencies and limitations in current attitude control systems. In long-duration or deep space missions, there are two common attitude control devices: reaction wheels (RWs) and control moment gyroscopes (CMGs). Three major shortcomings that stem from these devices are bearing failure and saturation in the RWs and gimbal lock in the CMGs. CELA combines the elements and properties of RWs and CMGs to create a reaction sphere (RS) which can be controlled and levitated. By using correlated electromagnetics (EMs) to levitate the RS, it eliminates the need for conventional bearings which cause friction and bearing failure. It also follows control laws through novel algorithms to avoid momentum saturation, and has no mechanical gimbals, eliminating gimbal lock.

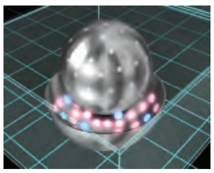


FIGURE 1. CELA prototype.

APPROACH/INNOVATION

This type of technology development is accelerated by an agile management approach. By focusing on a small subset of unknowns or objectives and catering tests to meet those requirements, they can be addressed effectively and thoroughly. After demonstrating that those requirements have been met, complete focus can be turned towards the next objective. This allocates time if needed to pivot the team's direction and schedule. By limiting each test cycle to 4–6 weeks, the schedule can be closely followed while allowing teams approximately a one-cycle schedule margin per year. This year, CELA's first test article demonstrated levitation of a single axis using a combination of permanent magnets and a zenith EM. A test cycle incorporating correlated permanent magnets and EMs helped in understanding their levitating abilities. In future cycles, the prototyping team will then rotate the axis, add a large disk, rotate the disk/axis combination, and add EMs on the disk's circumference and commutate the axis of rotation.

CELA differs from others by a decoupled bearing and drive system, a novel control algorithm, correlated EMs for precise regulation of the rotational axis and levitation, additive manufacturing of the mechanical bodies, and advanced magnetic dipole printing methods. It will also reduce the volume and mass of the attitude actuators and will be scalable to small and large spacecrafts that comprise the command, control, and communications networks and relays.

RESULTS/ACCOMPLISHMENTS

The prototyping of a levitating RS was conducted first. A 3D-printed hemisphere design's rotational control was observed using a hall effect sensor to control the balance and spin of the model. By positioning EM wire coils around the model, the model's rotation was tested. Magnetic levitation was explored next. A three-ring 3D-printed prototype was designed and assembled where each ring consisted of 12 EM wire coils allowing for levitation in three degrees of freedom (DOF). By using a circuit and programmed microcontroller, the coils could be turned on and off to control the levitation of a test magnet. Excessive heating of the circuit and weak EM coil magnetic properties were identified and corrected by the team. So far, the levitation of a magnetic axis has been tested with one

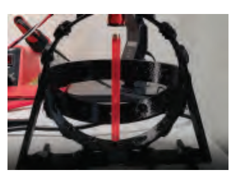


FIGURE 2. Levitation of a single axis.

DOF, and testing for the second DOF will be conducted soon by the University of Alabama in Huntsville (UAH) senior design team.

The Florida Institute of Technology (FIT) controls team developed equations, MATLAB scripts, and Simulink models for each type of attitude control device to provide baseline performance comparisons of each to a spherical actuator. By comparing each device's simulation, it helped determine issues with desaturation and loss of attitude control. The team developed a pyramidal CMG simulation to model the compensation of spacecraft attitude for small angle commands in three directions. Next, a Northrop Grumman (NG) RS model simulation took individual coil currents and current rotor positions to calculate the force and torque on each permanent magnet in the rotor. Finally, a hall sensor logic table helped determine the RS's orientation through rotor angle and position when given an input of hall effect sensors. Research in current levitation technologies has been conducted, but none of the current research was enough to fully baseline a levitation simulation. A new simulation has been modeled from scratch using an iron and air EM configured in three orthogonal sets with two pairs of opposing magnets; this will continue to be simulated in the future.

The Advanced Manufacturing (AM) team began by researching magnetic ink embedded in stereolithography (SLA) material to possibly use this technique to print EM designs. A 3D-printed spiral determined how small of a channel ink could get through. Unfortunately, uncured resin got trapped in spiral channels, making the ink unfit for the study. Neodymium plates were then tested to see if the plates' dipoles could be wiped without any damage. After thermally testing a plate in a box furnace at 850 °C for 1.5 hr, the plate's magnetic pattern was completely erased, but the coating and underlying magnetic material were damaged. The maximum Curie temperature of 400 °C was determined and used as the maximum temperature for the next test. The plate's magnetic pattern became erased and the plate did not sustain any damage. After this success, printing dipoles onto the plate's surface was the team's next goal. Pyramid magnets and a robotic arm mechanism were projected to precisely move the magnet around the plate's surface. Lifting force limitations of the robotic arm were determined and a rotating stepper motor was added to the arm to overcome the limitations while creating a more customizable assembly and magnet travel length. In the future, the use of the arm and mechanism will be tested to print dipoles on the plates.

The final system team, EM field modeling, has recently started COMSOL modeling. The necessary COMSOL modules being used to simulate EM fields are AC/DC, rotating machinery, and magnetic modules. By using these modules, different shapes can become associated with physics to develop a detailed time-varying model of EM fields dependent upon the positions, orientations, and magnetizations of the magnets. This modeling will help us understand how the magnetic forces interact to create levitation of the RS.

SUMMARY

CELA is a technology that eliminates the three main problems in current attitude control systems. The core of this technology revolves around the mechanical design and arrangement of discrete EMs. Research and simulations are being used to determine the necessary dipole patterns for stable controlled levitation. Prototype testing is also being done to miniaturize and precisely align

the EMs in an outer shell, interacting with a high-density array of permanent magnets embedded into the inner sphere. The development approach then improves upon previous prototypes of the CELA technology while introducing AM technologies to make the final system simpler, lower cost, and reproducible, and is key to developing new materials to fit certain properties for the stator and rotor. Controls and EM field modeling will be important in determining the best way to levitate and control the RS by understanding the limitations and EM properties through simulations.

PRINCIPAL INVESTIGATOR: Sarah Triana

PARTNERS: Florida Institute of Technology; University of Alabama, Huntsville

FUNDING ORGANIZATION: Center Innovation Fund

INDEX BY FUNDING SOURCE

Center Innovation Fund

Center Strategic Development Steering Group

Cooperative Agreement Notice

Game Changing Development

Operations Directorate Advanced Exploration Systems Division

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Technology Investment Plan

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Many of NASA's missions would not be possible if it were not for the investments made in research advancements and technology development efforts. The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. This annual Research and Technology Report features brief write-ups from the scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts, which are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

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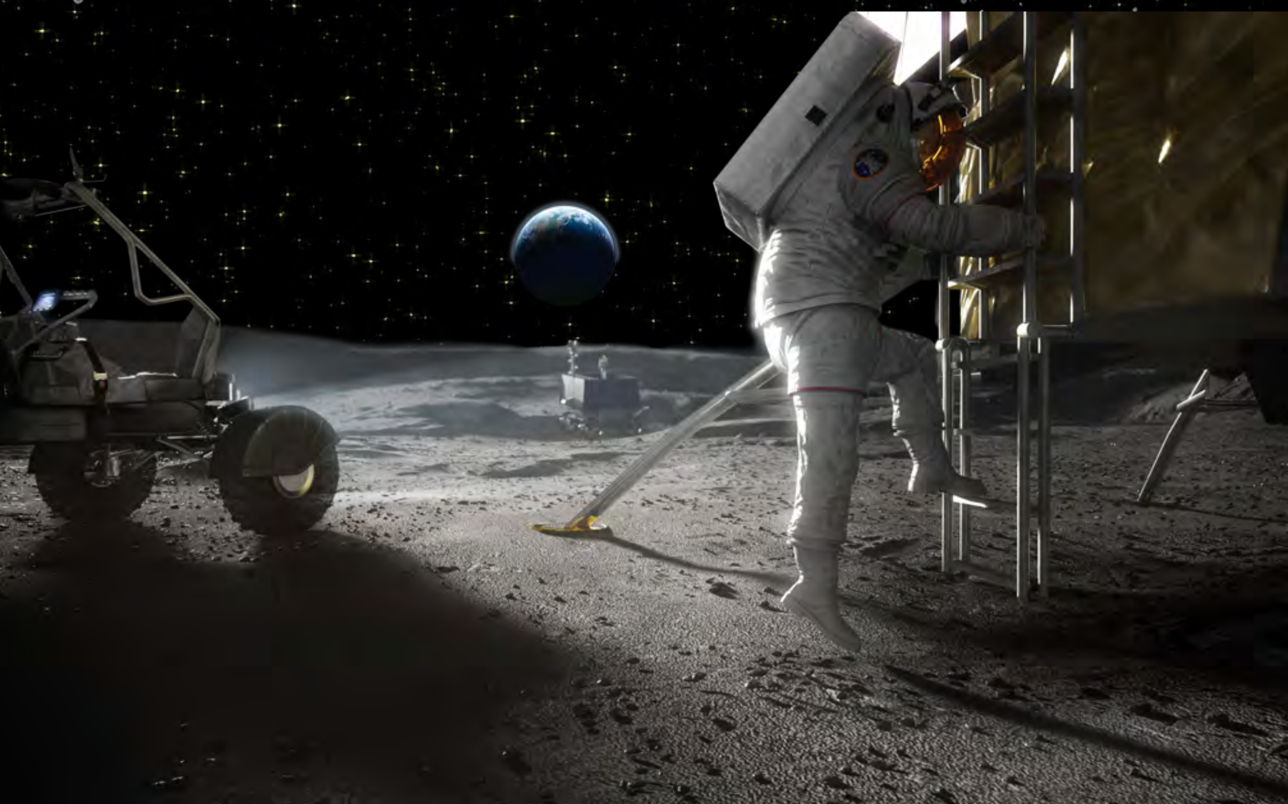

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